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ABSTRACT

This project explores the factors influencing the learning of classical mechanics, with an ultimate goal in improving instruction. Twelve academically gifted seventh and eighth graders were interviewed to test their previous perceptions about objects in free fall. They were then observed as they used physics laboratory apparatus and computer simulations to plan, execute, and analyze experiments. It was found that students' knowledge about the motion of objects in free fall can be characterized by distinctive sets of logically linked propositions. Designs and procedures for experiments devised by the students could be traced to some of their specific pre-instructional conceptualizations that the analyses of pretest interviews revealed. Schema theory is used to interpret the findings of this study and to speculate on their implications for instruction. (CS)

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INTERACTIONS OF STUDENTS' KNOWLEDGE WITH THEIR COMPREHENSION AND DESIGN OF SCIENCE EXPERIMENTS

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Abstract

The relationship between students' knowledge about the motion of objects and the students' comprehension of physics instruction is the topic of this paper. Students have considerable knowledge about the motion of objects, some of which is consistent with the physical concepts they are to learn and some which is not. The inconsistent prior knowledge can hinder learning rather than being a facilitative influence. The paper describes methodologies for systematically describing students' preinstructional knowledge concerning the motion of objects in free fall. A system of propositional analysis which was applied to students' protocols is described and illustrated. How the students' preinstructional knowledge about free fall relates to their subsequent learning of mechanics concepts is discussed. The paper should be of interest to cognitive psychologists, science educators, educational researchers, and instructional designers.

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INTRODUCTION

This research is part of an investigation into factors influencing the learning of classical mechanics. The general research goal is to uncover the sources of students' difficulty in understanding and applying classical mechanics principles with the ultimate goal of improving instruction. However, at this time we are not investigating instruction directly. The research reported here focuses on one potential source of instructional difficulty, the students' pre-instructional conceptions about how and why objects move in free fall.

This is not the traditional starting point for investigating instructional problems; however, in light of cognitive learning theory and our preliminary findings, the focus is justified. Furthermore, we hope to demonstrate that this focus can be a widely useful modification of the traditional approach to instructional problems. The order of topics, then, is: (1) rationale for the focus

on pre-instructional knowledge; (2) description of the research method and the instruments used to measure pre-instructional knowledge, (3) analysis of data and findings, and (4) summary and implications.

RATIONALE

The research reported here attempts a complete and accurate description of the learner's pre-instructional conceptions about the motion of objects in free fall, which is a focus of study in classical mechanics. However, within traditional instructional technology, based on work by Gagne and colleagues (1968, 1974), the most useful model of the learner depicts where the learner stands in relation to a norm. The relationship is often expressed by identifying the objectives which the learner has already achieved and those which remain to be achieved. The IPI model of individualization is the canonical example of this tradition (Lindvall & Bolvin, 1967).

This model is based on an interpretation of how pre-instructional knowledge interacts with learning, one strongly influenced by Gagne's theory of learning hierarchies for intellectual skills (1968). The only interaction of interest is positive transfer:

> In particular, specific responses transfer to discriminations, which transfer to classifications, which transfer to rules, which, in turn, may transfer to more complex forms of rule-governed behavior, such as that exhibited in problem-solving. (Gagne, 1968, p. 6)

However, positive transfer and a hierarchical organization are not characteristic of all learning; verbalizable knowledge, or "what the individual knows," for example, does not have a hierarchical organization (Gagne, 1968).

Nevertheless, instructional models incorporated only the positive transfer aspect of this theory into their structure of individualization. The subject matter to be learned was analyzed into behavioral objectives, the objectives sequenced on some rational basis, and the student pre-tested for the presence or absence of those behaviors. Instruction in the absent behaviors proceeded in the rational sequence. The interaction between the students' pre-instructional knowledge and learning from instruction was assumed to be always one of positive transfer. Simply put, a student who "knew" Objective 1 would more easily learn Objective 2 than one who did not.

It is now time, we believe, to clarify the parameters within which this instructional model is useful. We will argue that, specifically with regard to classical mechanics, and presumably for other subjects that resemble it, a more complete model of the learner's pre-instructional knowledge is required to design effective instruction, because a simple pattern of positive transfer does not describe the relationship between all pre-instructional knowledge and learning.

We have found the concept of "knowledge structures" as discussed in comprehension-of-text studies very helpful in operationalizing other types of interactions between pre-instructional knowledge and learning. In general, these studies indicate that text is not understood solely "on its own." Understanding and remembering text involves processing the text in terms of the reader's world knowledge or schemata (Bransford & McCarrell, 1974; Pickert & Anderson, 1977; Anderson, Reynolds, Schallert & Goetz, 1977; Chiesi, Spillich & Voss, 1979).

The concept of schemata, current in cognitive psychology, has an analogue in the "history of an organism" in radical behaviorism. For example, an

extensive behavioral analysis of learning from lecture is provided by Ferster (Ferster, Culbertson & Boren, 1975, pp. 563-568). He describes a hypothetical example of complete and accurate communication: two students work together on a problem--A achieves the solution just as B is about to achieve it, and A states it first. B is the ultimately prepared listener, one whose history with respect to the problem matches that of A, except for the final step--achieving the solution. In this unusual case, hearing (or reading) the solution enables B to understand the solution as A understood it.

Given Ferster's analysis, when the histories of speaker and listener with respect to the subject matter are identical, verbal communication is possible but not necessary; when they are widely divergent, accurate verbal communication is not possible. A situation in which the histories are highly similar but not identical is necessary for accurate understanding of the speaker/text by the listener/reader.

Schema theory has a remarkably similar interpretation of understanding text, although we will leave open the question of whether schemata are more than the history of the organism. In Anderson's words (Anderson, et al., 1977, p. 368), "the meaning of a communication depends in a fundamental way on a person's knowledge of the world and his/her analysis of the context as well as the characteristics of the message." More specifically, world knowledge, organized as a schema, is usually viewed as providing (1) a fairly abstract "scaffolding" which serves as the contextual organizing principle for interpreting the text; and (2) a basis for inferring details or elaboration from the text. "A reader correctly understands a text when the schemata embodied in the text by the author correspond to the schemata by which the reader assimilates the text." (Anderson, et al., 1977, p. 370)

Clearly, then, misunderstandings occur when schemata do not correspond. But, as Anderson's work (Anderson, et al, 1977) indicates, a text can be assimilated to more than one superordinate schema. A sense of understanding may occur whenever text is completely assimilated to a schema, regardless of whether the assimilating (reader's) and the embodied (writer's) schemata are identical. In this case, we have a misinterpretation, but one of which the reader is unaware.

In the case of a subject matter like classical mechanics, problems of misinterpretation and incomplete understanding seem particularly likely. Classical mechanics is about motion of macroscopic objects. Therefore, every student has had extensive daily experience with the objects of study. If schemata are formed from experience, then students have schemata for understanding motion before instruction. Furthermore, many of the terms used in classical mechanics are used in everyday life--terms such as acceleration, momentum, speed, and force. Unfortunately, the relationship between everyday experience and the formal structure of classical mechanics is not simple or direct. Dijksterhuis (1961), an historian of science, argues quite strongly that the axioms of Newtonian mechanics are, at best, unrelated to intuitions about motion derived from everyday experience:

> Classical mechanics, with its principle of inertia and its proportionality of force and acceleration, makes assertions which not only are never confirmed by everyday experience, but whose direct experimental verification is fundamentally impossible; one cannot indeed introduce a material point all by itself into an infinite void and then cause a force that is constant in direction and magnitude to act on it; it is not even possible to attach any rational meaning to this formulation (p. 30).

So in classical mechanics we face a situation in which the world experiences that students have available to interpret textual instruction are

inappropriate. The text purports to be about motion, it uses some familiar terms, but how is a student to interpret an axiom like this:

> If there is no net force acting on a body, it will continue in its state of rest or will continue moving along a straight line with uniform velocity (Williams, Trinklein & Metcalfe, 1976, p. 61).

Frank (1957), a philosopher of science, distinguishes between two aspects of physics, the formal system of Newtonian mechanics and the use of the formal system as a mechanism for producing a veridical description of the physical world. Logical reasoning has a place of prominence in the formal system. Sense observations have a place of primary importance in testing the validity of a formal system as a mechanism for describing the physical world. The logical validity of the formal system is not compromised if it does not produce an accurate description of the real world. The utility of the system to predict and describe the behavior of objects in the physical world is a separate issue.

The formal system is based upon axioms[1] (in the case of classical mechanics, Newton's Three Laws). Other propositions are derived from these axioms by the application of the formal rules of logic. These propositions have logical validity because of their form, without regard to the meaning of their terms. If the formal system is to have meaning, that is, for the conclusions drawn within its framework to be consistent with sensory observations of the physical world, the terms of the axioms must be defined operationally. Defining the terms acceleration, force, and mass, for example, is the first step in the process of establishing the meaning (making a physical interpretation) of the formal system. Frank (1957) asserts that:

> The cause of much misunderstanding among students of physics is the fact that most textbooks do not mention that this law [inertia] is meaningless unless an operational definition of its terms is given. The same problem exists also with respect to the second law—'acceleration' with respect to what?....In most elementary textbooks and courses on

> mechanics the terms rectilinear motion and acceleration are bluntly used without even a hint that a physical system of reference to which these terms refer must be given. (pp. 104-105)

This analysis by Frank helps to emphasize the importance of precise use of technical vocabulary when the formal system of mechanics is being applied to physical situations and raises several interesting theoretical and practical questions related to instruction and learning. What meaning do students at different levels of development attribute to the technical vocabulary of mechanics? What happens during the instructional process when the "everyday" meaning of these terms is mapped onto the formal application of Newton's Laws? Can the technical meaning of the terms be understood apart from the understanding of the formal system? These are some of the questions that dictate the direction of our research into science instruction and learning.

METHOD AND INSTRUMENTS

Subjects

Twelve academically-talented[2] seventh and eighth grade students participated.

Selection Process

They were selected by representatives of the Allegheny Intermediate Unit (AIU) from a pool of 46 students who were nominated by their school districts. The districts were asked to nominate academically-talented students with self-expressed interest in science and mathematics to participate in an unstructured, enrichment experience with opportunities to manipulate physics

apparatus and to use a computer. Selection criteria applied by the AIU representatives were pragmatic. Only two girls were nominated and both were selected. Other students were selected primarily on the basis of demographic characteristics of the districts they represented, the intent being to serve populations of different racial and socio-economic composition.

Experimental Setting

Two rooms at the Learning Research and Development Center (LRDC), were used by the students, who were engaged in investigating a problem in physics. The problem was to determine the rules describing the motion of the A-machine (Figure 1). One room contained equipment and supplies that could be used to construct versions of the A-machine differing in several important dimensions (mass of block, mass of bucket of sand, frictional force between the surfaces). Equipment also was available for investigating other phenomena related to the motion of objects in free fall and under the influence of constant force.

In a second room, computer simulations of experiments with the A-machine were available. The simulations were presented on a graphics scope and Datapoint 3300 terminal, both driven by LRDC's PDP 15 computer. A complete description of the simulation is in Appendix A.

Procedure

The students were divided into two groups of six students each. The composition of the groups was arbitrary except that the two girls were placed in the same group. The study extended over a sixteen-week period. During this time the students came to LRDC on alternate Mondays from 9:00 a.m. to 2:30 p.m. There were three sources of data relating to the students' mental

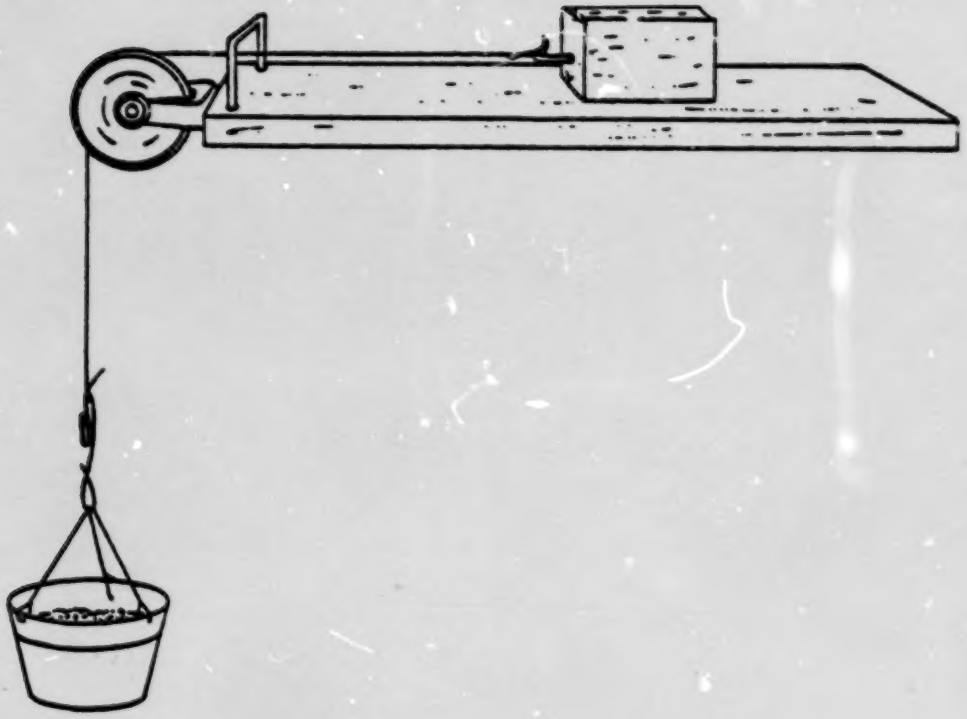


Figure 1. The apparatus consists of a block of wood, a flat board with a pulley attached at one end, a string and a bucket of sand. The block of wood rests on the board and is connected to the suspended bucket of sand by the string which runs over the pulley.

representations of knowledge concerning the motion of objects: student performance on the DOE (Demonstrate, Observe, and Explain) Tasks; student performance on the ConSAT (Concept Structuring Analysis Technique) Task; and the systematic observation of students as they planned, executed, and analyzed experiments.

The DOE and ConSAT Tasks data were gathered during the first two sessions and the observational data relating to student-generated experiments were gathered over the remaining seven sessions.

DOE Tasks Administration

The DOE Tasks have students predict the results of a physical demonstration, explain their prediction, and describe their observation of the demonstration. They provide information on students' conceptions about motion, and on their rationalizations for the conceptions. The DOE Tasks are administered in a group setting. They consist of demonstrations of the motion of various objects under the influence of a constant net force. The same general format is followed for most of the demonstrations. The experimenter first displays the apparatus that will be used and describes the demonstration that will be performed. The student is asked to predict the result of the demonstration. After writing the prediction, the student writes out the basis on which the prediction was made. The demonstration is then performed and the student records what he/she observed. The student notes any inconsistency between the prediction and the observation and attempts to explain how he/she might resolve the inconsistency. The two DOE Tasks analyzed in this report are called: (A) DOE Task on the Speed of a Single Object in Free Fall, and (b) DOE Task on Two Falling Objects of Unequal Mass.

ConSAT Task Administration

The ConSAT Task provides information about the student's understanding of the technical terms of mechanics, specifically their definitions and relations to each other. The ConSAT Task is administered individually. The student is given a stack of cards, each with one term on it that a physicist might use to describe the motion of an object (kinematics) or to explain the cause of observed motion (dynamics). Sixteen terms were used: mass, weight, volume, density, object, time, distance, speed, position, velocity, acceleration, force, pressure, work, energy, power. The student reads each term aloud and decides if he/she recognizes it. (If the student has difficulty pronouncing the term, the experimenter pronounces it correctly.) If the student recognizes the term, he/she is asked to define it. Unrecognized terms are set aside. When all terms have been sorted and the recognized terms defined, the student arranges the recognized terms on a large sheet of paper in a way that shows how he or she "thinks about them." When the student completes the arrangement of the terms, he/she is asked to explain why the terms are arranged in that way and to specify the relations among individual terms or groups of terms. Finally, the student reviews the unrecognized terms. Any term that the student now recognizes is defined and placed in the structure.

This interview is recorded on audiotape. In addition, the experimenter writes notes directly on the paper describing the students' explanations for the arrangement, and any changes made in the arrangement during the course of the administration.

Student-Generated Experiments

Following the administration of the ConSAT Task and the DOE Tasks, the

students were given the problem that they were to investigate, namely, to determine the rules that describe the motion of the A-machine (see Figure 1). A few simple procedural constraints were placed on the students to facilitate data gathering for this phase of the study. Students were required to describe experiments that they wanted to do, to provide a rationale for the experiment, and to predict the outcome of the experiment.

The instructors did not act as authorities. Rather, they asked leading questions and tried to help the students design experiments or develop logical arguments based on group-generated empirical evidence. One strategy used to develop an awareness of the students' knowledge was to ask students to define any terms they used. Another strategy was to encourage "thought experiments" which could not be performed.

ANALYSES AND FINDINGS

This part of the report contains three major sections. The first two describe the analysis of the DOE Tasks and the ConSAT Task, and what we learned from these analyses about the students' preinstructional knowledge of the motion of objects in free fall. The third section discusses our analysis of the observations on student-generated experiments related to the motion of objects in free fall.

DOE Tasks

Descriptions of the motion of objects in free fall and the causal explanation of the motion are among the first topics to which students are exposed in the study of physics. Two of the DOE Tasks are designed to probe students' knowledge about objects in free fall. The first DOE Task concerns the

motion of an object falling vertically in the earth's gravitational field. The second DOE Task concerns the comparison of the motion of objects of different mass and congruent shapes in the earth's gravitational field.

DOE Task on the Speed of a Single Object in Free Fall

The apparatus for this DOE Task consists of a chalkboard eraser and a stand holding a one-meter wooden pole which is banded with red tape near its top, blue tape about half-way down, and green tape near the bottom. After the experimenter describes the demonstration, he holds the eraser next to the band of red tape and releases it. The students are asked to observe the eraser as it passes the blue and green marks. The demonstration is repeated two or three times, and the students write their responses to these questions:

1. When the eraser falls from the red mark to the floor, how does its speed as it passes the blue mark compare with its speed as it passes the green mark?

2. What did you consider in order to answer that question?

Appendix E contains an explanation of the background physics behind the two DOE task demonstrations. It also contains an alternative explanation based on common student answers. Readers whose physics knowledge is rusty may wish to refer to the appendix in order to better understand our analysis of the students' responses.

We are interested in three features of the students' responses to those questions.

Acceleration in free fall. The first feature of interest is whether or not the students are aware that, under the conditions of the demonstration, the eraser undergoes constant acceleration. It should be noted that it is doubtful that the acceleration (change in velocity) of the eraser can be observed visually, so this "observation" is influenced by what the students believe about the motion of the eraser.

Use of a force analysis. The second feature of interest is whether the student explains acceleration or its absence through an analysis of the forces acting on the eraser. A force analysis provides a causal explanation of motion. A feature of the organization of instruction in classical mechanics is the distinction between the description of motion and the cause of motion. The study of how objects move, or the description of motion, is kinematics, and the study of why objects move, or the causes of motion, is dynamics.

Nature of the students' analyses. The third feature of interest is the analyses the students themselves offer. Here we are interested in identifying the intuitions, authoritative or informal knowledge, and the modes of reasoning the students apply to their analyses and interpretations of the physical situations. The distinction between authoritative and informal knowledge is not wholly precise but, as our discussion will reveal, this distinction has important instructional implications. One type of informal knowledge consists of a general rule abstracted from inappropriate examples or from an incomplete set of examples. An example of informal knowledge of this type is the general rule that light objects fall more slowly than heavy objects. The "evidence" for the rule is the observation that feathers fall more slowly than bricks. An

example of authoritative knowledge is the rule that all objects, no matter what their weight, fall at the same rate when dropped from a height. There are many counter-examples to this rule, and yet students will defend its validity on the basis of having learned it in school or having read it in a book.

The degree to which the students put forth a logical argument to defend their analysis of a physical situation also has important instructional implications. Some investigators have asserted that students' inability to learn physics is simply a function of their inability to think logically. Our analysis of the present data suggests that incorrect conclusions which appear to be the result of illogical reasoning, in fact, may be the result of logical reasoning based on incorrect assumptions or incomplete information.

Of theoretical and instructional interest also, is the extent to which students base their interpretation of a physical situation on observation. Our hypothesis is that students' observations are influenced by their conception of the situation, and our analysis provides information that is relevant to this hypothesis.

Data Analysis for the First DOE Task

Many aspects of the data analysis are quite straightforward. The students' descriptions of the motion are generally quite explicit and easily interpreted. Nevertheless, a few procedural ground-rules were necessary to produce consistent analyses.

The following criteria were applied to determine if the student's response is a force analysis. The explanation is scored as a force analysis if: (1) terms from dynamics are used, and (2) the nature of the relationship between the

force and the resulting motion is explicit. So, for example, "the eraser fell because gravity pulled it down" uses a force term (gravity) and specifies the nature of the relationship (pulled). But "the eraser fell because of gravity" fulfills only one condition and is not scored as a force analysis.

In determining whether or not the student claimed to be basing his or her response on observation and in categorizing the knowledge (authoritative or informal) on which a response was based, the student's self-report was used. Achieving some degree of objectivity concerning the content and form of the arguments the students put forth required a more formal analysis. For this purpose, the students' statements were translated into formal symbolic propositions. The translation of student protocols was achieved through the application of the following procedures. Four members of the research team, who were familiar with the students and their instruction and who had studied the DOE Task protocols, decided on a set of rules for constructing propositions and on a glossary for the symbols. Then, each person individually coded the protocols. Comparisons of the individual codings showed approximately 95% agreement on the assignment of symbols and approximately 70% agreement on propositions constructed from the students' responses. Discussions of the coding discrepancies and the interpretation of the proposition constructing rules enabled the four persons to reach a consensus on the formal symbolic propositions represented in the protocol of each student.

Selected examples of the verbatim student protocols and their corresponding formal symbolic propositions from the DOE Task on the Speed of a Single Object in Free Fall are listed in Table 1. These examples were selected to display the full range of formal propositions derived from this DOE Task. They also offer quite clear illustrations of how the translations from protocols to formal

Table 1

Examples of the Propositions Extracted from Student Protocols for the DOE Task on the Speed of a Single Object in Free Fall

Subject	Verbatim Protocol	Explicit Propositions	Inferred Propositions
SD	The speeds are the same when it passes the blue mark and when it passes the red (sic) mark. I considered what I saw and that I think I remember the pull of gravity always stays the same no matter whether the object is just starting to fall or has been falling for a time.	$S_b = S_g$ $F_G \not\propto t$	$F_G \not\propto d$ $S \propto F_G$ $S \not\propto t$ $S \not\propto d$
DC	When the eraser fell, the speed of it passing the green mark was significantly greater than its speed when passing the blue mark. ... I considered the time the eraser took to fall two similar distances based upon my observation while the experiment was in progress.	$S_g > S_b$ $d_{rb} = d_{bg}$	$t_{rb} > t_{bg}$ $S = \Delta d/\Delta t$
ST	The speed of the eraser increased as it went from the blue to the green, because the distance from red to blue is less than red to green. The greater the distance the faster the speed.	$S_g > S_b$ $d_{rb} < d_{rg}$ $S \propto d$	
TM	The eraser went faster as it passed the green mark than the blue. The speed the eraser picked up as it came closer to the ground, the gravitational pull became greater.	$S_g > S_b$ $S \propto d$ $F_G \propto d$	$d_{rg} > d_{rb}$ $S \propto F_G$

propositions were accomplished. The complete set of propositions for all students for the first DOE Task is given in Appendix C.

A full glossary for the symbols used in Table 1 is in Appendix B. Nevertheless, the symbols are quite straightforward and can be briefly summarized. S, d, t, and F_G stand for speed, distance, time, and the force of gravity respectively. Subscripts r, b, and g refer to the red, blue, and green markers used to indicate vertical positions in the demonstration of this DOE Task. The symbol "$\propto$" means "is roughly proportional to." It is used to express the notion that, as one variable of a pair increases, so does the other, all other things being equal, but a strict mathematical relationship (such as, a doubling of one will double the other) is <u>not</u> necessarily implied. To symbolize the inverse of this relationship, that as one variable increases, the other decreases, we use a reciprocal expression such as '$x \propto 1/y$' but, again, this does not imply necessarily that the product of x and y is constant. Lastly, a diagonal slash through any symbol indicates negation.

The propositions in Table 1 are divided into two types: those that were explicity stated in the students' protocols and those that could be inferred.[3] The basis for constructing inferred propositions varied considerably. An example of a "near" inference, based on the demonstration's context, can be seen in DC's protocol. DC asserts that the speed was greater at the green mark than at the blue and justifies the answer by saying, "I considered the time the eraser took to fall two similar distances, based upon my observation, while the experiment was in progress." DC says explicitly that he compared two times, but he does not explicitly mention what the two times are, or how they compared. Fortunately, from the context, it is apparent that he compared the time it took the eraser to fall from the red mark to the blue mark, and found it to be

greater than the time to fall from the blue mark to the green mark. This inferred proposition is entered as $t_{rb} > t_{bg}$ in Table 1.

An example of an inferred proposition which logically relates two propositions in a protocol can also be seen in DC's initial answer to the question. DC utilized the concept "speed." However, when justifying the answer, DC introduces the concepts "distance" and "time," but does not mention speed again. Presumably, there is a relationship here between the concepts mentioned in the justification and in the initial answer. In this case, the inferred proposition is that "speed" is "distance" divided by "time," or $S = \Delta d / \Delta t$.

Yet another class of inferences are logical consequences of previous propositions. An example of this is seen in the protocol of SD, who says that "the pull of gravity [on the eraser] always stays the same, no matter whether the object is just starting to fall or has been falling for a time." From this, we can extract the explicit proposition that "the force of gravity on the eraser does not change with time as the experiment progresses," or in symbols: $F_G \nmid t$. Since distance changes as the time changes, the proposition that "the force of gravity on the eraser does not change with distance as the experiment progresses," that is, $F_G \nmid d$, can be inferred.

Findings for the First DOE Task

Table 2 presents data relating to the students' awareness of increasing velocity in free fall. Ten of the twelve students state that the eraser travels faster at the green (bottom) mark than at the blue (middle) mark. None of the AIU students gave evidence of considering the possibility of terminal velocity. Table 3 presents a breakdown of the types of explanations given by the students

for this situation. An explanation is classed as a force analysis if the nature of the relationship between the force and resulting motion is reasonably explicit. If terms from dynamics are used in the explanation, but the nature of the relationship is left unclear, the explanation is scored as uninterpretable. (It might be seen as an incomplete attempt at a force analysis.) An explanation that simply restates the prediction is classed as descriptive, since it is nearer to kinematics than to dynamics. On this basis, 4 of the 12 students used a force analysis.

Table 2
Frequency of Students' Awareness of Acceleration in Free Fall
in Responses to the First DOE Task

"The eraser's speed..."	n
is constant	2
increases	10
increases to terminal velocity	0
Response Uninterpretable	0

Table 3
Frequency of Students' Use of a Force Analysis in Responses to the First DOE Task

Type of Explanation	n	Student Codes
descriptive	6	HT, KQ, DC, ST, NJ, LL
force analysis	4	SD, FO, TM, DX
uninterpretable	2	MD, WD

In the responses to the first DOE Task, only two instances were observed where students explicitly indicate that they used some authoritative knowledge in their explanations. Student KQ asserted that the speed of the eraser increases as it falls, and his explanation related that he considered what "Galileo said, which is that falling objects increase their speed in relation to the time they have been following [sic]." Student SD, who asserted that the speed of the eraser remains the same as it falls, also wrote that:

> I think I remember the pull of gravity always stays the same no matter wether [sic] the object is just starting to fall or has been falling for a time.

It is interesting to note that, in both instances, the students were unsure either about the authority's name or the content of the authoritative knowledge they were citing.

Propositions used in students' arguments. As the findings in Table 2 show, the students in this sample asserted either that the eraser's speed in free fall increases or that its speed is constant. They were, respectively, either "accelerators" or "non-accelerators." Table 4 shows the key formal propositions in the arguments of both the "accelerators" (left-hand column) and the "non-accelerators" (right-hand column). This table also serves as a brief overview for the ensuing discussion in this section of the formal propositions used by the students.

The formal proposition for the assertion of the "accelerators" is that the speed of the eraser at the green mark is greater than its speed at the blue mark. Expressed in symbols, this proposition is: $S_g > S_b$. This assertion is supported by the three key propositions given in the first column of Table 4.

Table 4

Key Propositions in the Student Protocols for the DOE Task on the Speed of a Single Object in Free Fall

"Accelerators" - Students Who Assert that:		"Non-Accelerators" - Students Who Assert that:	
$S_g > S_b$	The speed of the eraser at the green mark is greater than its speed at the blue mark	$S_g = S_b$	The speed of the eraser at the green mark is equal to its speed at the blue mark.
$S \propto t$	The speed of an object in free fall is proportional to the length of time it falls.	$S \not\propto t$	The speed of an object in free fall is not proportional to the length of time it falls.
$S \propto d$	The speed of an object in free fall is proportional to the distance it falls (measured from the release point).	$S \not\propto d$	The speed of an object in free fall is not proportional to the distance it falls (measured from the release point).
$S \leftrightarrow F_G$	The speed of an object in free fall is related to the strength of the force of gravity on the object.	$S \leftrightarrow F_G$	The speed of an object in free fall is related to the strength of the force of gravity on the object.
$F_G \propto d$	The strength of the force of gravity on an object in free fall is proportional to the object's position (distance from the release point). (Equivalent to: the force of gravity increases as the object approaches the ground).	$F_G \propto d$	The strength of the force of gravity on an object is not proportional to the object's position (distance from the release point).

These key propositions represent the essential components of the "accelerators'" logical argument for their assertion. A parallel set of key propositions is shown in the second column of Table 4 for the "non-accelerators" who assert that $S_g = S_b$. What we have, then, are two reasonably straightforward sequences of key propositions that distinguish and clearly contrast the arguments of the two groups. The "accelerators" who assert that $S_g > S_b$ can be characterized by one set of formal propositions in their preinstructional knowledge structures, while the "non-accelerators" can be characterized by contrasting formal propositions. This is one important result of the student protocol analysis.

Table 5 presents a summary of all the formal propositions that appear in the students' protocols. Except where noted in the table, the propositions are in the order that the student wrote them. The students are grouped according to two criteria: (1) whether or not they state that objects in free fall accelerate, i.e. "accelerators" and "non-accelerators," and (2) whether or not they rely heavily on information from observations. As shown in Table 2, 10 of the students state that the eraser's speed at the green mark is greater than its speed at the blue mark. Table 5 indicates that 8 of these students base their assertions on reasoning alone, one on purported observations alone, and one on both reasoning and observations. Two students are "non-accelerators," but one gives an uninterpretable explanation. The other states that he bases his belief on a sequence of reasoning, rather than on the observation that the speed is the same at the two points. It should be noted that, in fact, it is highly unlikely that the students were able to make accurate observations. However, students who claimed to make observations tended to use only propositions describing the concrete empirical relationships in free fall, rather than using the more abstract propositions concerning explanatory relationships.

Table 5

Summary of Explicit and Inferred Propositions for the DOE Task on Speed of a Single Object in Free Fall

"Accelerators" - Students Who Assert that $S_g > S_b$

A. Assertion Based on Reasoning

$S_g > S_b$	TM	FO	DY	WD	MD	ST	KQ*	NJ	LL
$d_{rg} > d_{rb}$	(TM)	FO*	(DY)	WD*	(MD)	ST	(KQ)	(NJ)	(LL)
$S \propto d$	TM	FO	DY	(WD)	(MD)	ST	KQ	NJ	LL
$S \nleftrightarrow F_G$	(TM)	FO	DY	WD	MD				
$S \propto F_G$	(TM)	(FO)	(DY)	WD					
$F_G \propto d$	TM	(FO)	(DY)						
$(F_G \propto t)$									

B. Assertion Based on Observations

$S_g > S_b$	DC	LL
$S = \Delta d/\Delta t$	(DC)	LL
$d_{rb} = d_{bg}$	DC	(LL)
$t_{rb} > t_{bg}$	(DC)	(LL)

"Non-Accelerators" - Students Who Assert that $S_g = S_b$

$S_g = S_b$	SD
$d_{rg} > d_{rb}$	(SD)
$S \not\propto d$	(SD)
$S \nleftrightarrow F_G$	(SD)
$S \propto F_G$	(SD)
$F_G \not\propto d$	(SD)
$F_G \not\propto t$	SD

* - proposition appears out of order in the protocol.

() - proposition was inferred from the statements explicitly in the protocol.

There are three notable features of the propositions and arguments listed in Table 5. One is that reading the propositions in reverse order from bottom to top produces a conclusion about the velocity of the eraser as it falls. For example, if you assume that the force of gravity is proportional to the distance travelled and that speed is proportional to the force, then you can conclude that the speed is proportional to the distance travelled. From there, you can quickly derive that the speed at the green mark is faster than the speed at the blue mark. As one reads up the list, from bottom to top, the propositions structure a logically connected, well-formed argument. An intriguing finding, which Table 5 illuminates, is that, by and large, the students mentioned these propositions in the exact opposite order.

The second feature is that the propositions that compose the arguments of the "accelerators" are the complements of the propositions that compose the arguments of the "non-accelerators," and the third is that the propositions are linked in a logical order. For each relationship between a pair of terms in the "accelerators'" argument, there is a corresponding relationship in the "non-accelerators'" argument. However, for most propositions, the relationship in one argument is the negation of the relationship in the other.

The students' conception of the relationship between speed and force that is revealed by the protocols provides some explicit empirical data to support the contention of physics instructors that students' ideas about motion are Aristotelian. The motion-force relationship in the Aristotelian perspective is that motion is caused by force. The Newtonian perspective is that changes in an object's speed or direction of motion are caused by an unbalanced force on the object. One goal of physics instruction is to engender a Newtonian perspective in students. More exact specification of the cognitive characteristics of the

Aristotelian perspective is important in designing effective instruction to attain this goal.

The protocols provide striking evidence that students intuitively link motion and force. The DOE Task questions asked the students about the eraser's speed--a question that can be answered on the basis of empirical evidence alone without any reference to the cause of the motion. However, half of the students introduce the concept of force when asked about the knowledge that they used to answer the question about the eraser's speed. Specific "Aristotelian" links between motion, force, and speed that the students generate are: (1) where there is motion, there must be a force acting; and (2) when the speed of an object changes, it is because the force on the object has changed.

The propositions that the students generate contain the terms "speed" and "force," and we have evidence that these incorrect links between the terms derive, in part, from the meaning that the students attribute to the terms and relations in the propositions. From our analysis of the ConSAT Task (detailed elsewhere in this report), we know that for these students speed and rectilinear motion are essentially synonomous. Speed is the exclusive measure of motion, even though the students are aware that in some situations objects change the speed or direction of their motion. The AIU students do not differentiate between average and instantaneous speed. Given the nature of the definition of speed, the "logic" of the link between speed (motion) with force is obvious.

There is an equally flexible definition of the relationship between speed and force. The meanings students attribute to "related to" or "proportional to" are quite ambiguous. Thus, the general rule induced by the students that speed is proportional to force is quite consistent with everyday experiences that share important features with the DOE Task demonstration. However, some

students infer a more specific relationship between speed and force. They link constant speed with constant force, and they assume that speed is directly (algebraically) proportional to the magnitude of the force. Direct evidence for this line of reasoning comes from SD, the student who thought that objects fall at constant speed. His rationale for this conclusion is that the constant speed of a falling object is the result of the constant force of gravity.

The students' resolution of the belief that objects in free fall accelerate with the conception that constant speed implies constant force produces a very interesting misconception for three of the students in this group. The misconception is that the force of gravity on the falling object increases as the object gets closer to the earth. We call this the "gravity gradient" misconception.

Almost all of the AIU students have heard that objects increase in speed as they fall. This knowledge is inconsistent with the belief that constant speed implies constant force. One way to resolve the inconsistency is to abandon the idea that constant speed implies constant force and replace it with the idea that constant force produces constant acceleration. This is the Newtonian resolution. Applying this solution to the DOE Task demonstration, one would say that the falling eraser increases its speed at a constant rate, i.e., it undergoes constant acceleration, because it is under the influence of a constant force (gravity).

An alternative resolution of the inconsistency is to assume that the force increases. This solution results in the observed gravity gradient misconception. Three of the AIU students (TM, FO, DX) explicitly state that the force of gravity on the eraser increases as the eraser gets closer to the earth, thus resolving the logical inconsistency between some knowledge they possess

(and probably didactically learned) and an intuition derived from their experiences with the real world. It is important to note that the origin of the misconception is a logical resolution of a conflict and that the conflict is the result of partial learning or incomplete instruction. The gravity gradient misconception was also expressed explicitly several times by other AIU students during the instructional period of this study as they were designing and explaining their experiments. In this context the students further justified their misconceptions by noting that, after all, there is /no gravity in outer space. These students believe that the change in the force of gravity in the one-meter drop of the eraser is considerably greater than the one part in 1.6×10^{13} that it actually is. They are surprised when the force is too small to influence the reading on a vertically-held spring scale as it is moved from the room's ceiling to the floor.

Presumably, the students haven't explicitly been taught the gravity gradient concept, so we may assume that they have invented it. As such, we can ask: What purpose does it serve? The concept only serves a purpose if it provides a solution to the predicament of wanting to believe simultaneously that a constant force produces a constant speed, and that objects increase their speed in free fall. There is no other circumstance in which the gravity gradient misconception has value.

Lastly, some comments can be made on the order of the propositions in the students' arguments. As we noted above, the propositions that compose the students' arguments are logically connected. Read from the bottom up, i.e., reversing the order in which the students gave their arguments, they produce as a conclusion the students' assertion about the speed of the eraser. We have two hypotheses concerning this inverse order phenomenon. One is that the questions

were worded in such a way as to emphasize this order of responding by first asking for an answer and then asking for a justification. The other is that the students naturally start with their concrete knowledge and progressively induce the abstract generalized propositions.

Despite the great diversity in the details of the students' responses, two consistent features of the reponses are most striking. Almost all of the students justified their knowledge about the motion of the eraser in free fall with a proposition that related speed and distance travelled. Moreover, those who went beyond this empirical proposition and attempted a causal explanation followed a line of logical reasoning to an incorrect proposition about the force of gravity. One additional significant observation (which takes on even greater importance in the findings for the second DOE Task) is that inertia was never mentioned, either explicitly or implicitly, by any of the students in their causal explanations.

DOE Task on Two Falling Objects of Unequal Mass

In this DOE Task, students predict the outcome of a demonstration and give reasons for their predictions. After the demonstration they report what they observed and note whether or not it accords with their prediction. Finally, if the observation and prediction are discrepant, they explain the discrepancy.

The DOE Task on Two Falling Objects of Unequal Mass probes the students' understanding of the relationship among the force of gravity on an object, its mass, and its free-fall velocity. The experimenter displays two blocks of equal dimensions but different mass and describes the demonstration he will do: the blocks will be released from the same height (about 100 cm above the floor) and at the same time. Then students write their answers to these two questions:

1. Predict how the time it takes for the aluminum block to fall from the red mark to the floor compares with the time it takes for the lucite block to fall from the red mark to the floor.

2. On what basis did you make your prediction?

After the experimenter drops the blocks as described several times, students answer these questions:

3. What did you observe?

4. If your prediction was incorrect, what reasons can you now give to explain your observation?

Appendix E contains a brief explanation of the cannonical account of the physics behind the second DOE Task, and an alternative explanation based on common student answers. Readers may wish to refer to Appendix E to refresh their knowledge of this task.

Data Analysis for the Second DOE Task

The two prediction questions provided most of the data for the analysis. Four features of the student protocols are of interest. These are: (1) the prediction about the relative speeds of the two objects of congruent shape and different masses; (2) the use of a force analysis; (3) the use of authoritative knowledge; and (4) the characteristics of the propositions and arguments the students use to rationalize their predictions and the discrepancies between their observations and used in analyzing these features in the protocols of the first DOE Task on the Speed of a Single Object in Free Fall.

The analysis of the characteristics of the propositions and arguments began

with the translation of the students' predictions. The analytical procedures for the first three features are the same as those written responses to these questions into equivalent formal propositions, as was done in the first DOE Task. A detailed description and examples of that translation for the present DOE Task follow.

The process of translation of student protocols into explicit and inferred propositions is described here. Table 6 provides four instances of verbatim protocols and the corresponding explicit and inferred propositions.[4] A complete set of explicit and inferred propositions for falling objects of unequal mass is in Appendix D. A complete table of the symbols used in propositions is in Appendix B. In general, superscripts indicate the specific object under discussion (t^A indicates time for the aluminum block), and subscripts indicate points at which observations are taken (t_f indicates the final time of the block, which is the time it hits the floor). The use of two subscripts indicates that the variable of interest is the interval between those two points. So, t_{of} refers to the time interval between the moment of release and the final moment of travel for the block.

Propositional analysis. The third column of Table 6 provides an explicit propositional translation of the verbatim protocol in the second column. In general, the translation begins with the first sentence and proceeds to the last. Exceptions to this order occur when an earlier sentence only becomes translatable in light of a later one. KQ provides an example. His second sentence, "Gravity has an equal effect on things" is not easily translated into propositions because "effect" and "things" are ambiguous. It is not clear if the "effect" refers to a force or to the motion of objects. Hence, no explicit propositions about gravity are derived at this point. The last sentence, "They

Table 6

Examples of the Propositions Extracted from Student Protocols for the DOE Task on Two Falling Objects of Unequal Mass

Subject	Verbatim Protocol	Explicit Propositions	Inferred Propositions
WD	**prediction:**		
	The two blocks will take the same amount of time to reach the bottom. All masses reach the bottom at the same time providing that there is no air resistance and that they are dropped at the same time and height.	$t_{of}^{A} = t_{of}^{L}$ $m^1 \neq m^2$ $t_f^1 = t_f^2$ if $d^1 = d^2$ and $t_o^1 = t_o^2$	$d/t_{of} = S$ $t_{of} \not\propto m$ $S \not\propto m$
KQ	**prediction:**		
	They will both land at the same time. Gravity has an equal effect on things. They were both at the same height. They were pulled down at the same rate.	$t_f^A = t_f^L$ $d^A = d^L$ $S^A = S^L$ $S \leftrightarrow F_G$	$d/t_{of} = S$ $F_G \not\propto m$ $S \not\propto m$ $t_{of} \not\propto m$ $S \propto F_G$
MD	**prediction:**		
	I think the aluminum block will fall faster and hit the ground before the lucite block. Because the aluminum block is heavier, so it would have a stronger pull of gravity.	$S^A > S^L$ $t_f^A < t_f^L$ $w^A > w^L$ $F_G^A > F_G^L$ $F_G \propto w$	$d/t_{of} = S$ $w = m$ $S \propto m$ $F_G \propto m$ $S \propto F_G$
	observation:		
	I saw the aluminum block and the lucite block both hit the ground at the same time. Because the gravity pull was the same.	$t_f^A = t_f^L$ $F_G^A = F_G^L$	$F_G \not\propto m$ $S \propto F_G$
TM	**prediction:**		
	The aluminum block will fall faster because of the greater weight, gravity will make the aluminum fall faster. From my experience, such as a brick compared to a feather. The brick will fall faster.	$S^A > S^L$ $w^A > w^L$ $S^A \propto w^A$ $F_G \leftrightarrow S^A$ $S^{brick} > S^{feather}$	$d/t_{of} = S$ $w = m$ $t_{of} \propto m$ $S \propto m$
	observation:		
	From all that I could see, they fell at about the same rate. I think that I was thinking that they were closer in weight than I thought.	$S^A = S^L$ $w^A \simeq w^L$	$S \propto m$

were pulled down at the same rate," provides a clue about the "things" on which gravity has an "effect." These two sentences emerge as two propositions, $S^A = S^L$ (the speeds of the aluminum and lucite blocks are equal) and $S \leftrightarrow F_G$ (the free fall speed is related in some way to the force of gravity.)

The set of explicit propositions retains most of the information in the student protocol. If, for example, a student talks about the time it takes the blocks to fall, the explicit propositions use the symbol t_{of} (see protocol for student WD, for example). If, instead, the student refers to the time the blocks land, the symbol t_f is used (student KQ). And if the student's focus is on the rate of fall, the symbol S is used (students MD, TM).

Once a set of explicit propositions has been agreed upon as representing one protocol, that set is examined to identify "inferred" propositions. Propositions may be inferred on several bases. The simplest basis is equivalence of referents. For example, if we have reason to believe that students do not distinguish between "speed" and "time to fall a given distance," and a student explicitly relates one of these concepts to "distance," the other referent is similarly related to distance in the set of inferred propositions. Referents which we consider equivalent include:

1. "speed" and "time to fall a given distance"

2. "weight," "mass," "density"

Evidence that the students do not distinguish among these referents comes from DOE Task protocols and ConSAT Task performance.

A second basis for an inferred proposition is that the proposition can be used as a logical generalization from the set of explicit propositions. For

example, from WD's statement that "all masses reach the bottom at the same time..." we can logically infer the generalization that an object's speed in free fall is not proportional to its mass, all other things being equal, although WD does not explicitly make this generalization.

A third and closely related basis for an inferred proposition is its logical necessity in linking the prediction and explanation. For example, MD gives two reasons for the prediction that the aluminum block will fall faster than the lucite: (1) the aluminum block is heavier; and (2) it has a stronger pull of gravity. From this we infer that the relationship between an object's speed in free fall and the object's mass is roughly a direct proportion ($S \propto m$), and the object's speed is related to the "strength" of the pull of gravity in the same way ($S \propto F_G$). Similarly, KQ predicts that the blocks will land at the same time because "gravity has an equal effect on things." Again, we can infer that the relationship between the pull of gravity and the speed of an object is roughly a direct proportion.

Findings for the Second DOE Task

As shown in Table 7, seven of the students predict that the times will be equal and four predict that the aluminum block will hit the ground first. A comparison of the information in Tables 7 and 8 reveals that all of the students who predict that the aluminum block will hit first attempt a force analysis. Only two of the students who predict equal times attempt a force analysis. As we will note later, both of these students make incorrect statements about the relationship between the force of gravity and an object's mass. (Gravity pulls equally on all things, regardless of the mass.)

Table 7
Frequency of Students' Predictions of the Objects' Relative Times in Free Fall in Responses to the Second DOE Task

"The times will be. . ."	n	Student Codes
equal	7	WD, NJ, LL, KQ, ST, HT, SD
different	4	
aluminum shorter	4	FO, MD, DC, TM
lucite shorter	0	
Uninterpretable	1	DX

Table 8
Frequency of Students' Use of a Force Analysis in Responses to the Second DOE Task

Type of Explanation	n	Student Codes
Descriptive	5	WD, NJ, ST, HT, SD
Force Analysis	6	LL, KQ, FO, MD, DC, TM

Four students explicitly report (see Table 9) that they use information that they had "learned somewhere" or made reference to an authority in defense of a prediction. All four of the students had predicted that the time of fall for the two blocks would be the same. One of the students makes an interesting appeal to authority— "Somebody a long time ago dropped a feather and a brick from a certain height and they hit at the same time."

Table 9
Students' Use of Authoritative Knowledge in Responses to the Second DOE Task

Student Codes	n
LL, NJ, ST, SD	4

Propositions used in students' arguments. The key propositions used by students to support their predictions are presented in Table 10 as an introductory overview of the important findings from this section. All but one of the students predicted either that the aluminum and lucite blocks would hit the floor at the same time, or that the aluminum block would hit the floor before the lucite block. These two predictions are expressed as formal propositions, in both symbols and words, at the head of the two columns in Table 10.

No student explicitly states all four propositions in support of a

Table 10

Key Propositions in the Student Protocols for the DOE Task on Two Falling Objects of Unequal Mass

Group I	Students who Predict that:	Group II	Students Who Predict that:
$t^A = t^L$	The time for the aluminum block to fall to the floor equals the time for the lucite block.	$t^A < t^L$	The time for the aluminum block to fall to the floor is less than the time for the lucite block.
$t_{of} \not\propto m$	The time an object takes to fall a given distance is not proportional to the mass of the object.	$S \propto m$	The speed of an object in free fall is proportional to the mass of the object.
$t_{of} \leftrightarrow F_G$	The time it takes an object to fall a given distance is related in some way to the force of gravity.	$S \leftrightarrow F_G$	The speed of a falling object is related in some way to the force of gravity.
$F_G \not\propto m$	The force that gravity exerts on an object is not proportional to the mass of the object.	$F_G \propto m$	The force that gravity exerts on an object is proportional to the mass of the object.
$F_G = k$	The force of gravity is constant for all objects, regardless of their mass.	$F_G^A > F_G^L$	The force of gravity on the aluminum block is greater than the force of gravity on the lucite block.

prediction. Nevertheless, the four propositions supporting each prediction are internally consistent and, furthermore, no student uses a proposition inconsistent with that supporting set. This consistency of propositions across students provides evidence for the existence of a main line of reasoning in support of each prediction. The two lines of reasoning are explicated later in the analysis. As an introduction to the analysis, one important finding must be pointed out. Both lines of reasoning agree on one point, that the speed of an object in free fall is related in some way to the magnitude of the force that gravity exerts on the object. As more detailed analyses will show, a rough proportionality characterizes this relationship in both lines of argument.

Table 11 summarizes the explicit and inferred propositions given by ten of the twelve students in support of their prediction.[5] In this table the propositions are grouped thematically. The first propositions transcribe the student's prediction. The question was posed as a comparison of the "time to fall" for the lucite and aluminum blocks ($t^A = t^L$ or $t^A < t^L$), but some students made a prediction in terms of speed instead ($S^A = S^L$, $S^A > S^L$). The possible significance of this distinction is discussed later.

The second set of propositions are remarks about the experimental conditions. We assume that all students recognize the features of the experimental conditions that are explicitly described before the demonstration: (1) the distance that the aluminum block would fall equals the distance the lucite block would fall ($d^A = d^L$); (2) the experimenter would release both blocks at the same time ($t_0^A = t_0^L$); and (3) the mass of the aluminum is almost twice as great as the mass of the lucite block ($m^A > m^L$). Given that all students are aware of these three conditions, the conditions that they explicitly mention provide a clue as to what features of the situation they

Table 11

Summary of Explicit and Inferred Propositions for the DOE Task on Two Falling Objects of Unequal Mass

	Group I Students							Group II Students			
	KQ	LL	SD	WD	NJ	ST		MD	DC	TM	FO
Prediction:							**Prediction:**				
$S^A = S^L$	E						$S^A > S^L$	E	E	E	
$t^A = t^L$	E	E	E	E	E	E	$t^A < t^L$	E			E
Experimental Givens:							**Experimental Givens:**				
$d^A = d^L$	E	E	E	E			$d^A = d^L$				
$t_o^A = t_o^L$		E		E		E	$t_o^A = t_o^L$				
$m1 \neq m2$			E	E	E		$m^A > m^L$	E	E	E	E
Empirical Propositions:							**Empirical Propositions:**				
$S \not\propto m$	I						$S \propto m$	I	I	E	
$t_{of} \not\propto m$	I	I	I	I	E	E	$t_{of} \propto m$				E
Force Analysis:							**Force Analysis:**				
$F_G = k$		E					$F_G^A > F_G^L$	E	E		
$F_G \not\propto m$	I	E					$F_G \propto m$	E	E		
$S \leftrightarrow F_G$	E	I					$S \leftrightarrow F_G$			E	
							$F_G \leftrightarrow t_{of}$				E

E - explicit proposition in protocol

I - inferred proposition in protocol

believe to be important. The equal-time and unequal-time groups clearly differ in the features mentioned. Again, the possible significance will be discussed later.

The third set of propositions is empirical, while the fourth set presents the students' force analysis, which are causal explanations for motion. Six students use force terms to attempt a causal explanation of their prediction for falling objects of unequal mass.

Force of gravity is related to speed. The force analysis propositions of these six students (KQ, LL, MD, DC, TM, FO) fall into one of two lines of reasoning, depending on their prediction. Students who predict that the blocks will take the same amount of time to fall equal distances (KQ and LL) reason that the force of gravity is not proportional to an object's mass. The causal explanation for the predicted equal speeds is that the force of gravity is "equal," and since speed is related to force, then neither force nor speed is related to mass. Students who predict the aluminum will fall faster than the lucite (MD, DC, TM, and FO) say that the aluminum block has a greater force of gravity acting on it because the aluminum has a greater mass than the lucite. In other words, the force of gravity on an object is proportional to the mass of the object and directly related to the predicted free-fall speed of the object. Perhaps the most interesting characteristic of these apparently opposite lines of reasoning is their shared proposition. All students giving a force analysis agree that the force of gravity is related in a similar way to the speed of the object in free fall. The nature of the relationship can be inferred from the reasons given for each prediction. Students who predict equal speeds for objects of different mass state that the force of gravity is independent of mass, while those who predict that the heavier object will fall faster state

that the force of gravity is proportional to mass. In both cases, the force of gravity appears to be roughly proportional to predicted speed in free fall, all other things (like volume and air resistance) being equal.

Further evidence for the shared nature of the proposition comes from the four students who reported that, contrary to their prediction that the aluminum block will fall faster, both blocks appear to hit at the same time. Two of these students retain the belief that speed is proportional to mass, by suggesting that experimental conditions were not optimal for detecting this effect. One says the blocks were not sufficiently different in mass, the other that the distance of 100 cm was "too small." Yet, two students immediately state that gravity must pull "the same" on all objects regardless of mass, a proposition characteristic of the students who predicted equal times. It seems unlikely that students would, on the basis of one observation, take a new theoretical position that had nothing in common with their old one. But if these two theories share a fundamental proposition as we believe they do, the sudden switch becomes plausible.

The speed/time distinction provides additional, albeit indirect, support for an underlying relationship between speed and force in the student's belief systems. We have evidence from the DOE test protocols and the student experimentation that the relationship between speed, time, and distance is familiar to these students and that they can easily convert from "speed" to "time to fall a given distance." The use of one or the other concept in an explanation may be determined by a combination of task directions and the students' perception of the situation.

The question on falling objects of unequal mass is asked in terms of time. From Table 11, it is clear that students who respond in terms more closely

allied to speed are also more likely to use a force analysis. Four of the six students who use force terms make their prediction in terms of speed (KQ, MD, DC, TM). The actual words used are "speed," "rate," and "fall faster." Another of the students, FO, uses the words "quicker to the floor." This is transcribed as referring to time, but a speed interpretation is plausible particularly since he uses the word "motion" later to explain the discrepancy between the prediction and observation. The sixth student, LL, unequivocally analyzes the situation only in terms of time ("they hit at the same time") as do the four students who use no force terms in the explanations (SD, WD, NJ, ST). Thus, it seems that if a student thinks about this situation in terms of the speeds of the two blocks, he or she is very likely to bring in the concept of force and relate it to speed. Conversely, if the student thinks about the situation in terms of the time of impact for the blocks, he or she is unlikely to use the concept of force. The stability of this effect remains to be tested. For the present, it provides intriguing but weak support for the hypothesis that students relate speed and force.

Table 11 also shows that the prediction a student makes is a reliable indication of the elements of the experimental situation subsequently described. Students who predict equal times-to-fall will usually mention the equal distances as an important aspect of the experimental situation. Two of these students relate a version of the historical anecdote about Galileo dropping a cannon ball and a musket ball from a tower window (LL, SD).

On the other hand, none of the students predicting that the aluminum block will fall faster than the lucite mentions equal distances. The most salient aspect of the situation for them is that the mass of the aluminum block is greater than the mass of the lucite block. At this point, however, these

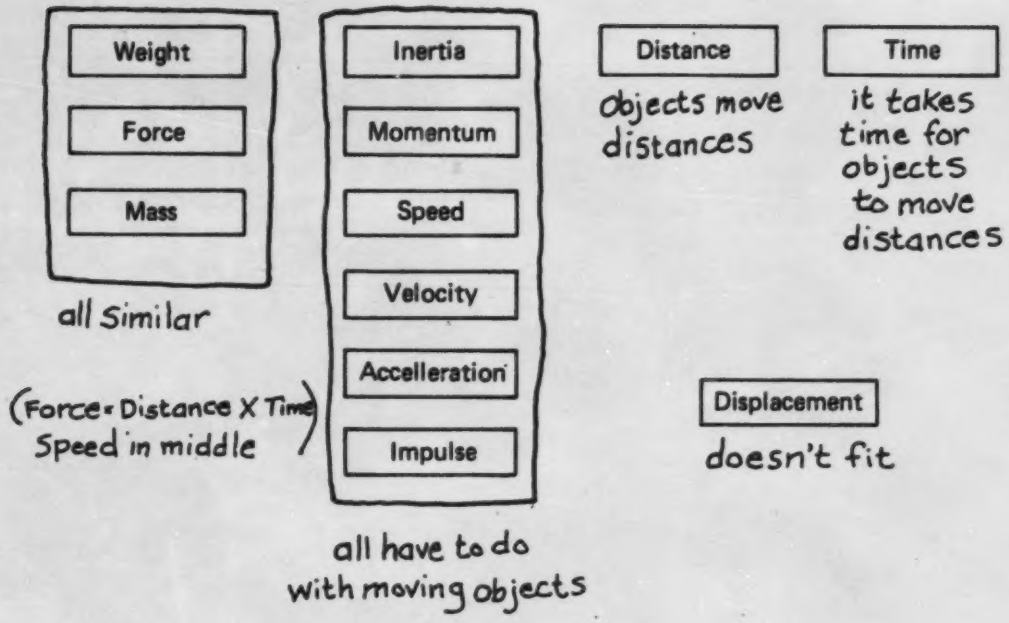
differences do not seem to have psychological significance.

Inertial mass. Another important feature of the force analysis propositions for both predictions is the absence of the concept of inertial mass. Students believe either that the aluminum block with more mass will fall faster because gravity pulls it harder, or that it will fall as fast as the lucite block because gravity pulls "the same" on both. The concept of inertia, that a greater force must be exerted on a larger mass to impart the same motion to it as to a smaller mass, is never applied to this situation. Unfortunately, no other formal tests for the concept of inertia were used, so we do not know if students would use the concept to explain horizontal or upward motion. A planned revision of the DOE Test instrument will include such tests.

ConSAT Task

The ConSAT data analysis procedure determines the extent to which the student (1) differentiates the meanings of physics terms, and (2) organizes them into an integrated structure. The administration of the ConSAT Task yields a definition for each of the recognized physics terms and a structural representation of the student's organization of the terms. Included in the structural representation are student-generated relations between pairs of terms and descriptions that characterize clusters of related terms. An example of a student's pre-instructional structural representation of the physics terms in the ConSAT Task is included in Figure 2.

In this representation the student has three clusters of terms. Each cluster is labeled by a term or phrase that describes a common feature or the relationship among the terms in the cluster. The student places weight, force,



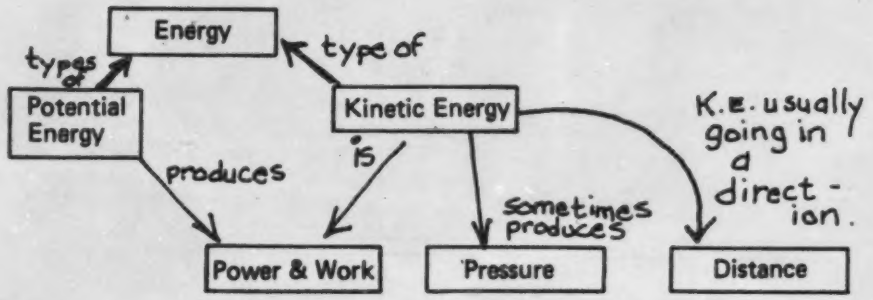


Figure 2. The arrangement of mechanics terms (ConSAT) done by a middle school student. The three basic clusters of terms found in this arrangement are typical of novices.

and mass in the same cluster because they are "all the same;" that is, they are equivalent terms. The student indicated that the cluster of six terms including inertia, momentum, speed, velocity, acceleration, and impulse was formed because "all has [sic] to do with object moving." In each of these instances, the student generated the descriptive phrase. The energy cluster is headed by a term, energy, that was part of the ConSAT Task. Included in this cluster of seven terms are student-specified relations between terms. For example, two relationships involving kinetic energy generated by the student are (1) kinetic energy is power and work; and (2) kinetic energy "sometimes produces" pressure. This brief examination of one student's structural representation should serve to introduce the reader to the ConSAT data on which the analyses of the students' definitions and structuring of terms are based.

Data Analysis: Definitions

The standard against which students' definitions of terms are matched is the physicist's definition. There are different levels on which these terms can be defined by the physicist. For example, a concept may be defined verbally or mathematically. The definition may be expressed mathematically in a relatively simple algebraic function or in the form of a differential equation. Assessment of the match between the students' definitions and the many possible forms of the technical representation provides information about both the accuracy and completeness of the student-generated definition.[6]

An important aspect of the analysis is to determine the degree to which students differentiate terms that have features in common but whose technical meanings are distinct. For example, in everyday use, velocity and speed are

interchangeable. Technically, they are distinct terms. The common feature of the terms is that both are measures of the change in an object's position over time. The feature that distinguishes the terms is that velocity is a vector quantity. A description of an object's velocity includes both the object's speed and its direction. The student who states that velocity and speed are the same has not made the technical differentiation. The student who attributes magnitude of speed as well as direction to velocity has differentiated the term in a way that is consistent with the technical definition.

Data Analysis: Structures

The structural representations are analyzed to determine (1) the structural characteristics of the representation; (2) the specific relationships between paired terms; (3) the dimensions that describe clusters of terms; and (4) relations among clusters of terms. The standard representation, against which student representations are analyzed, has the terms linked into a single integrated network. Our assumption is that the network structural organization best represents two features of the formal relations among these terms in the context of classical mechanics. In the formal system of classical mechanics, each of the terms has a unique meaning and is linked to the network composed of all other terms by well-specified (mathematical) relationships. The network structure represents both the differentiation of the terms and their integration. Figure 3 illustrates the network structure for selected terms from the mechanics ConSAT Task. This is the structural representation produced by an expert, a full professor of physics. Given that the network organization best represents the differentiation in meaning and the integration of the terms, it

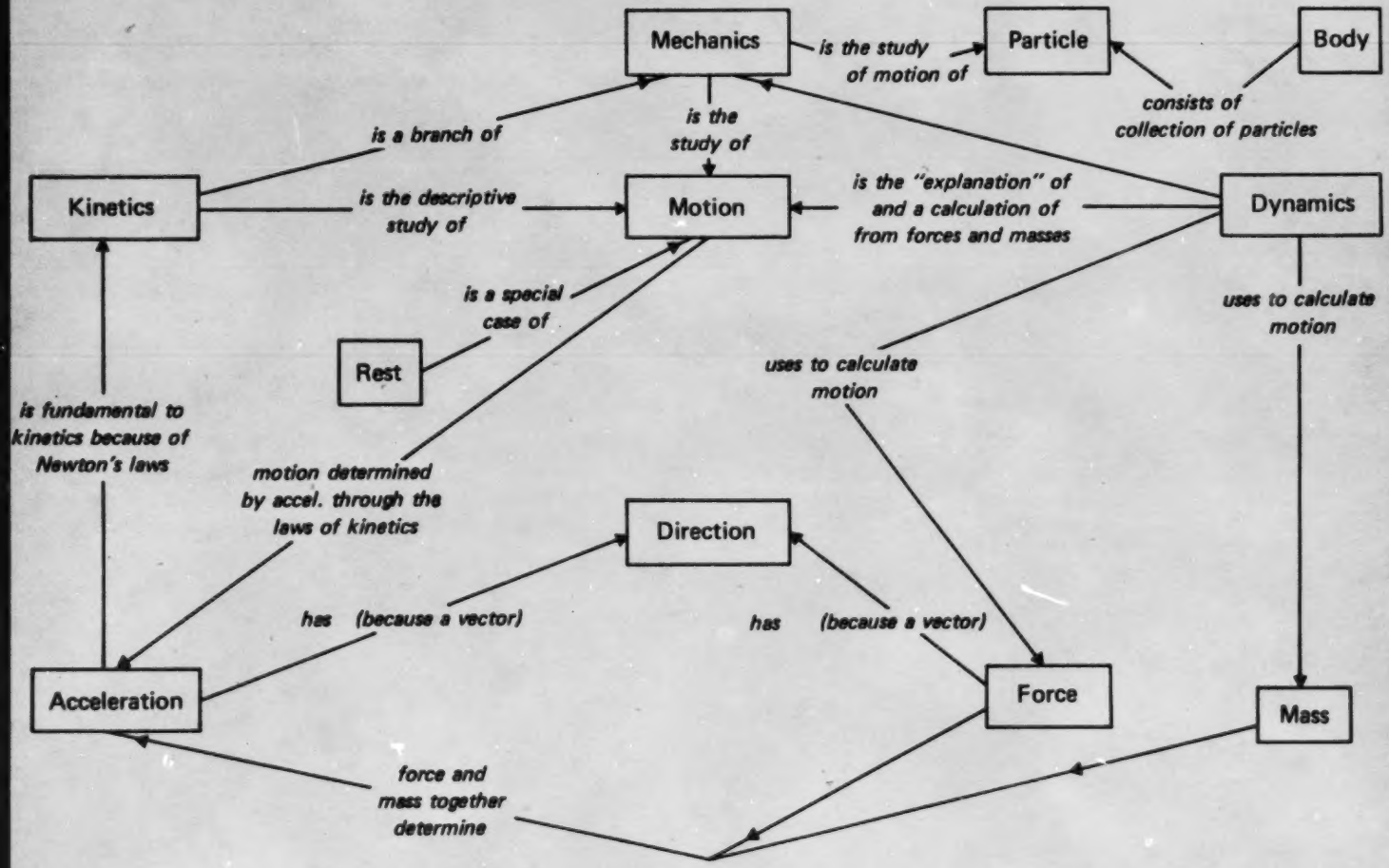


Figure 3. The arrangement of mechanics terms (ConSAT) done by a full professor of physics.

follows that structural representations of individuals who recognized terms but did not differentiate them would consist, not of the network organization, but rather of clusters of terms with the terms in each cluster having some feature in common. The network organization is characterized by relations among individual terms while the cluster organization is characterized by relations among clusters of terms.

From the foregoing discussion, it is evident that the particular structural characteristics of every student's representation can be identified. Similarly, no matter what the over-all structure of a representation may be, it is possible to analyze the specific relationships between terms which are paired and to examine the consistency of the relationships with the canonical interpretation of mechanics. However, only in those instances where the terms are structured in clusters, rather than a network, can the dimensions that distinguish clusters of terms be identified and the relations among clusters examined.

Findings: Definitions and Structures

Although the analyses of the students' definitions and structuring of terms proceeded separately, it is advantageous to present the findings from the two types of analyses together. This is particularly true in light of the first noteworthy finding from the analysis of the structural characteristics of the students' representations. It turns out that, of the 12 students, only one arranged the ConSAT Task terms in anything approaching a network structure. The clearly preferred organizing mode was to cluster terms into groups having some commonality or interdependence. The student's structural representation shown in Figure 2 is representative of this preference.

The context of the students' responses to the ConSAT Task was consistently scientific. Their definitions of terms seldom involved alternative non-scientific meanings (for example, some people make decisions on impulse, reading is hard work for kids, mass is celebrated in church), although some everyday meanings that bordered on the scientific meanings were used (for example, a football team that is playing well has momentum). The students tried to relate as many of the terms as possible and in some instances added terms to complete their ConSAT structures. Terms added by students were movement, volume, density, and object.

Terms in the students' structures cluster around three dimensions: (1) the physical properties dimension which serves to cluster terms that describe the physical characteristics of objects; (2) the kinematics dimension which serves to cluster terms that describe the motion of objects; (3) and the dynamics dimension which serves to cluster terms that are used to describe the causes of motion or the physical characteristics of objects due to their motion. Analysis of the students' definitions of terms and the way in which the terms are structurally organized in the students' representation shows that:

1. All twelve of the students organized the terms in a way that loosely corresponds to the three dimensions described above.

2. Only in one or two instances did a student give any evidence of differentiating between members of these pairs of terms: mass and weight, velocity and speed, or velocity (speed) and acceleration.

3. Only one of the students linked force and acceleration and the link was a tenuous one.

The details of each of these findings follow. The findings will be discussed in the light of the significance of particular terms for understanding

the motion of objects in free fall.

Velocity, speed, and acceleration. Particularly important to the systematic study of the motion of objects are the terms speed, velocity, and acceleration. All three of these terms are used to describe the motion of objects and one (acceleration) is the essential conceptual link between kinematics and dynamics. All of the students have some idea of what the term speed means, and two (WD and ST) give the formula definition that speed is distance travelled divided by the elapsed time. Eleven of the students explicitly relate velocity to speed, either by simply connecting them with a line, or by verbally describing their relationship. Examples of the described relationships are: "Velocity is speed or close to it" (TM), "With speed you get a certain velocity " (SD), "Velocity is like speed" (HT). Only one student (WD) explicitly states that velocity specifies both a speed and a direction.

Analysis of the ConSAT representations reveals some interesting information concerning the students' conceptions of the term acceleration. None of the students state that acceleration is a change in the speed and/or direction of motion. A majority of the students (7 out of 12) state that acceleration is an increase in speed. Acceleration is also given other meanings. WD states that objects accelerate when they are going "full speed." It is unclear if "full speed" refers to a terminal speed (uniform speed) or to the maximum motion (varying speed) for a certain force. Three students (SD, HT, TM) use acceleration to refer to the process of transforming an object at rest into an object in motion. The majority of students give no quantitative description of acceleration, except for two students (KQ, FO) who state that acceleration is the ratio of distance travelled divided by the time elapsed. In all, five

distinct uses of the term by the students are identified:

1. Acceleration is identical to speed.

2. Acceleration is the initiation of motion, i.e., the change from the state of rest to the state of motion.

3. Acceleration is the state of increasing speed and, as such, is unquantified.

4. Acceleration is the net increase in speed.

5. Acceleration is speed in a specific direction.

In summary, the ConSAT data reveal that, although all 12 students recognize the term acceleration, none of them defines or uses it completely correctly. The multiplicity of uses for the term testifies that acceleration is neither a clearly differentiated nor precisely formulated concept for these students.

This interpretation of the status of the students' concept of acceleration is supported by other findings from the analysis of the DOE Tasks. Ten students described aspects of motion in the DOE Tasks in which objects "go faster and faster" or perform some variant of the five meanings of acceleration identified in the ConSAT analysis. For example, to explain the motion of the eraser in the DOE Task on a Single Object in Free Fall, FO said, "It gets faster because it picks up momentum." Interestingly enough, only one student actually uses the term acceleration: WD said, "The force of gravity accelerates the eraser, and since the green mark is farther down, it takes longer to reach the green mark than it does blue, so more acceleration takes place." It seems likely that most of the students, not being cued with the technical terms in the DOE Tasks, prefer to use non-technical language to describe these situations. All

together, then, ten students use some partial concept of acceleration in responding to the DOE Tasks, but none of the students' usages is complete or precise or approaches the meaning of acceleration as the rate of change of velocity. Moreover, two students neither mention the term nor use any sort of concept of acceleration anywhere in their DOE Tasks protocols.

Mass-Weight. The distinction between mass and weight is an important issue in the formulation of classical mechanics. In everyday usage, however, these terms are rarely distinguished. On 11 of the 12 student representations, the terms mass and weight are linked. The only student who does not make this link thinks that mass is synonomous with atomic weight. Three students (NJ, ST, WD) think that mass is equivalent to volume, that mass times density equals weight and that the bigger the mass (of a given substance) the bigger the weight. About half of the remaining students think that mass and weight are the same and the others express vague awareness that the terms are used differently. These students associate weight with how hard gravity pulls on an object and express vague awareness that mass is somehow independent of the pull of gravity.

Force and Inertia. Force and inertia are two central concepts in establishing the link between the description of an object's motion and explaining the causes of the motion. A central feature of classical mechanics is the link between force and acceleration, but that association occurs only once in the ConSAT data. In a definition, TM states that "acceleration is the starting force," which we interpret as "the force which starts objects into motion is called acceleration." Force seems to be a familiar but ambiguous term to the students. Force has many links to other ConSAT terms, especially abstract terms, like pressure, momentum, energy, impulse, and others. This suggests that among these terms that the students so poorly differentiate, force

is a central concept. Noteworthy is the fact that force is never linked with acceleration in the structural representations. Three students directly linked force with speed and one student (ST) explicitly states: "more force, more speed."

It appears that the students have almost no concept of inertia. Only six students recognized the term. One student (WD) gives Newton's First Law of Motion as a definition of inertia. Others define it as relating to things that are "not moving." In the students' structural representations, two students link mass (weight) to motion but neither describes the relationship between the terms. Four other students link mass (weight) to force or motion or both, but in ways apart from the concept of inertia. For instance, DC links weight with distance and force by the concept of torque, and ST links force to momentum which is composed of mass and velocity. Six students did not link mass and weight with any other term. In short, there is little evidence to suggest that the students had even a rudimentary concept of inertia. The failure to consider inertia is also evident in the DOE Tasks responses and during the instruction.

Student-Generated Experiments

Whenever the students were engaged in discussions or doing experiments, the investigators took notes on the students' activities and the ideas they expressed. From these notes, several incidents have been selected for presentation here to illustrate the relationship between the students' knowledge, as revealed through the DOE and ConSAT Tasks, and the experiments which they formulated. Three classes of experiments were available to the students in the learning environment of the project, and all three were utilized

at various times. The students' experiments included not only those carried out with physical apparatus, but also computer-simulated experiments, and thought experiments. The available physical apparatus included three set-ups of the A-machine (illustrated in Figure 1), an air track with riders, electric timers, a velocity gate, balances, spring scales, and an assortment of miscellaneous equipment usually found in school physics labs.

Most of the students' experiments were concerned with the A-machine apparatus, with its low-friction equivalent on the air track, or with its surrogate in the computer simulations. Other experiments were directly concerned with the motion of objects in a gravitational field. In formulating the latter experiments and also those with the A-machine, the students made use of their existing knowledge or beliefs about falling objects. The following sections describe how student-generated experiments were derived from their conceptions of several key ideas: the relationship between an object's mass and its velocity in free fall, acceleration, inertia, and gravitational force.

Mass and Free-Fall Velocity

Explaining why the rates at which objects fall are independent of their mass was an especially intriguing and persistent problem for the students. Their interest in this problem was first observed during the first session of the program when the DOE Tasks were administered. When the administration was completed, the students were told that they could experiment on their own with the equipment used in the DOE Tasks demonstrations to test out their predictions and observations. Several students did so.

One student (FO) grabbed the two blocks used in the DOE Task on Falling

Objects of Unequal Mass and weighed them on a balance. He had predicted that the aluminum block would fall faster than the lucite block, but his observations in the DOE Task demonstration apparently contradicted his belief that heavier objects fall faster. To resolve this contradiction, he reasoned that despite the difference in the materials from which the two blocks were made, they must be the same weight, because they fell at the same rate. He proceeded to test this hypothesis by weighing the two blocks.

Two other students (TM, MD) who also believed that heavier objects fall faster, experimented by dropping the blocks from a greater distance above the floor than the demonstrator had dropped them from. TM climbed onto a table and dropped the blocks while MD put her head on the floor to watch their fall. These students reasoned that the blocks had, in fact, fallen at different rates, but that the difference in descent times was too small to be observed over the short distance (approximately one meter) used in the original DOE Task demonstration. They tested this hypothesis by designing an experiment which used a more sensitive procedure, i.e., dropping the blocks from a greater height, to illuminate any difference in the blocks' rates of fall.

The students' continuing concern with the problem of objects which differ in mass falling at the same rate also was evident in discussions of experiments the students designed throughout the program. At one point during a class discussion, all the students agreed that two carts of unequal mass, but equal volume, would strike the ground at the same instant when dropped from the same height. When they were asked how the speeds of the carts would compare if the carts were rolled down an inclined place, only one of the six (NJ) argued that the velocities would be the same. The other students decided to convince NJ that he was in error by doing a demonstration.

The students' first impulse was to do the demonstration by tilting the table and sliding objects down it. However, frictional forces were obviously present, so the students switched to rolling objects down the inclined table. This was followed by letting the rider carrying different weights slide along the tilted air track. Their principal concern was to demonstrate that the velocity of an object on an incline is dependent on the mass of the object. This belief is logically consistent with the belief that the velocity of an object in free fall depends on its mass.

The observations in the demonstration for the DOE Task on Two Falling Objects of Unequal Mass were often questioned. Some of the students continued to believe that they failed to observe differences in the rates of fall because of the insensitivity of the experimental procedure. Their experiments were designed to demonstrate differences in the rate of free fall. This was to be accomplished by increasing the sensitivity of the experimental procedures by increasing the distance through which the objects dropped. They also placed their heads on the floor and either sighted along the floor or listened for the impact in order to better distinguish between times of impact.

It must be remembered that these experiments, far from being idle exercises for the students, reflected a real dilemma that they faced. As shown in the propositional analysis for the DOE Task on Two Falling Objects of Unequal Mass, the students' Aristotle-like conceptions that the greater downward force applied to the heavier object implies that its speed of fall must be greater is incompatible with the observation that the objects fall at the same rate. One way to resolve this dilemma is to design experiments which will discredit that observation.

Acceleration

As the analysis of both the DOE and ConSAT Tasks made evident, the students operated with multiple meanings of the concept of acceleration. Among these meanings, one popular idea used by several students considered acceleration in a non-quantitative way as a state of increasing speed. In the course of developing this idea more precisely, a student-generated experiment was devised that required the use of both a physical apparatus and the computer simulation.

The students wanted to know if the block on the low-friction, A-machine on the air track moved with "uniformly-accelerated motion." They used the velocity gates to measure the block's instantaneous velocity at evenly-spaced locations along the air track. From their data, they determined that the block accelerated. However, because they did not have velocity data at equal time intervals, they could not determine if the acceleration was uniform. This dilemma was resolved by doing a computer-simulated experiment in World 3, which is frictionless and operates according to Newtonian mechanics. The students had correctly determined that in World 3 the block moves with uniformly-accelerated motion. They then compared the results and noted that, for data collected either at equal distances (air-track) or at equal time intervals (computer), the acceleration was the same. This is an example of a student-designed experiment that answers a question that a physicist would not ask. From the student's perspective, however, the question is neither trivial nor irrelevant.

Inertia

Students' conceptualizations of inertia were also the source of several

interesting student-generated experiments. As the analyses of the ConSAT and DOE Tasks show, few of the students had a well-developed conceptualization of inertia. However, some of the students expressed the belief that it is more difficult to initiate horizontal motion in a heavier block than a lighter block. However, this effect was attributed by the students to the increases in friction between the block and table. If this assumption is true, the velocity of the block will be independent of the block's mass when the experiment is performed on a frictionless surface. Indeed, one student, when finding the minimum mass of sand required to start the block in motion on the air track, argued that it was not necessary to weigh the block since weight (mass) was not a variable which affects motion.

Gravitational Force

As the students sought to clarify their ideas about how objects are affected by the force of gravity, a host of thought experiments was performed. These involved massive objects falling in vacuo in outer space and on the surface of other planets. The students often talked about experiments on the moon or in orbit around the earth, topics which they found fascinating. When the students were asked what keeps satellites in orbit, WD gave this five-point answer:

1. There must be gravity in outer space because otherwise the satellite would move in a straight line. Instead, it curves and goes in a circle around the earth.

2. Gravity is always pulling toward the center of the earth, which is the same as saying that the gravity is always pulling inwards.

3. However, the motion of the satellite is not an inward spiral, but rather it is circular, neither getting closer nor farther from the center of the earth. Therefore, there must be a compensating force.

4. This compensating force is "centrifical force." Centrifical force is an

outward force associated with all circular motion. The amount of centrifical force "balances" the gravity, and this keeps the object from getting either closer to or farther away from the earth.

5. The circular motion causes the centrifical force. There is no centrifical force until there is circular motion. Linear motions do not create a force, only circular ones do. One cannot say that linear free-fall motion causes gravity.

The notion of a gravity gradient is an example of another conception held by the students of student-generated experiments. In the propositional analysis for the DOE Task on a Single Object in Free Fall, it was shown that the students who were "accelerators" accounted for the object's increase in speed by hypothesizing a gravity gradient. If acceleration occurs as an object falls, it can be explained by assuming that the force of gravity on the object increases as it approaches the ground. The students supported this notion of a gravity gradient near the earth's surface by pointing out that an object in outer space, a spacecraft, for example, has little or no gravity acting on it.

The first time that the students measured the velocity of the block at various positions on the A-machine, they noted that the block was accelerated. They concluded that the "motion-causing" force on the block was increasing as the bucket of sand came closer to earth. The increased force was attributed to a gravity gradient. The hypothesized gravity gradient had a considerable effect. Within one meter that the bucket dropped, there was a four-fold increase in velocity. The students predicted that the force of gravity was four times greater at table-top level than at the floor level. They then measured the force of gravity on the bucket using a spring scale at the floor and at the table-top level. Finding no perceivable difference, the students increased the height differential for their measurements, by measuring the force of gravity on the ground floor and on the ninth floor of the building. Only then, having still failed to find a perceivable difference, did they abandon the

gravitational gradient explanation for acceleration.

SUMMARY AND IMPLICATIONS

Major findings reported in the preceding section concerning students' pre-instructional conceptions about objects in free fall include:

1. Students' knowledge about the motion of objects in free fall can be characterized by distinctive sets of logically linked propositions.

2. In responding to the first DOE Task, most of the students (10 out of 12) assert that the speed of the eraser in free fall increases. They are categorized as "accelerators." The "accelerators'" assertions generally are supported by a logically consistent chain of propositions, and 8 of them report that they based their assertions on reasoning alone, not on observation.

3. When "accelerators" seek to explain their assertion that the speed of an object in free fall increases, they <u>logically</u> derive the misconception that the force of gravity on the object increases appreciably over a 1-meter distance as the object gets closer to the earth (the "gravity gradient" misconception).

4. Two students assert that the speed of the eraser in free fall remains the same, and they are categorized as "non-accelerators." There is some evidence that the assertion of the "non-accelerators" also is supported

by a logically consistent chain of propositions. The propositions used by the "non-accelerators" usually are the complements of the "accelerators'" propositions.

5. In responding to the first DOE Task, 4 of the 12 students use a force analysis, but 6 students attempt a force analysis in responding to the second DOE Task.

6. Two students report that they used authoritative knowledge in responding to the first DOE Task, while four students report that they did this in the second DOE Task.

7. In responding to the second DOE Task, 7 of the 12 students predict that the two blocks of unequal mass would hit the ground at the same time, and 4 students predict that the heavier aluminum block would hit the ground first. In either case, the students' prediction is supported by a logically connected chain of propositions.

8. A central proposition in the reasoning of the students, regardless of what they predict about the relative times of fall for objects of unequal mass, is that the force of gravity on an object is roughly proportional to its speed in free fall. This proposition is similar to the Aristotelian conception that the force acting on an object determines its speed.

9. Students who predict that the two blocks' times of fall would be equal

(a correct prediction) arrived via logically consistent reasoning at the incorrect proposition that the force of gravity on an object is not proportional to the mass of the object. In contrast, students who predict that the two blocks' times of fall would be unequal (an incorrect prediction) arrived via logically consistent reasoning at the correct proposition that the force of gravity on an object is proportional to the mass of the object.

10. In performing the ConSAT Task, the students do not arrange the mechanics terms in a network structure, as a physicist would be likely to do. Instead, their preferred arrangement is to cluster terms into groups they consider to have some commonalities, which generally represented these three dimensions: (1) physical properties, (2) kinematics, (3) dynamics.

11. The students, with rare exceptions, do not differentiate between the terms in these pairs: mass and weight, velocity and speed, or velocity and acceleration.

12. Acceleration is neither a clearly differentiated nor precisely formulated concept for the students, on the basis of both their performance on ConSAT and DOE Tasks.

13. There is virtually no evidence that the students possess even a rudimentary concept of inertia.

14. Designs and procedures for experiments devised by the students could be traced to some of their specific pre-instructional conceptualizations that the analyses of the DOE and ConSAT Tasks revealed. Conceptualizations so traced include the Aristotle-like belief that heavy objects fall faster than light objects, conceiving of acceleration in a non-quantitative way as a state of increasing speed, and the "gravity gradient" misconception.

15. When the students formulated and conducted experiments, their behaviors and comments often were consistent with the conceptualizations of motion they expressed in doing the DOE and ConSAT Tasks, but not always. The inconsistencies indicate that different aspects of the students' knowledge are tapped by the several sources of data.

Implications

Schema theory provides a useful framework for interpreting the findings of this study and speculating on their implications for instruction. We have evidence that students begin physics instruction with the ability to devise a well-connected argument from knowledge organized in a motion-of-objects schema that is tightly integrated and derived from experience. Analysis of the propositional knowledge used by the students when they confront the task of predicting and explaining the motion of an object under certain conditions provides insights about specific propositions that compose the schema. This information allows us (1) to define with greater precision the differences between the students' pre-instructional knowledge and the desired

post-instructional knowledge states; (2) to make predictions about interpretations students will place on instructional events; (3) to predict how difficult it will be to disabuse students of particular misconceptions they hold; and (4) to plan instruction that is effective in bringing about the conceptual revolution from the experience-based motion-of-objects schema to the formal Newtonian system of mechanics.

In contrast to the Newtonian system, which quantitatively links force and acceleration, our students' schemata share as a common characteristic a qualitative link between force and motion. The specific relations between force and motion or speed that are explicitly stated differ from student to student. However, the force-speed relations have pervasive effects. These relations directly influence the assimilation of new propositions to the schema and, through the process of logical argument, contribute to the formation of propositions that link the concepts of the schema in new ways.

For the purpose of planning instruction, it is important not only to know the concepts and propositions that exist in the student's schema but to have some knowledge of their origins. For example, in responding to the second DOE Task with the aluminum and plastic blocks, a student might apply a general rule derived from experience to predict that the aluminum block will fall faster ("after all, bricks do fall faster than feathers"). The causal analysis of this prediction based on the force-speed relationship generates the proposition that gravity pulls harder on the heavier object. This proposition is consistent with the Newtonian formulation, but it is predicated on an empirical rule that is inappropriately applied to the situation the student is analyzing. On the other hand, the student who has learned or been told (as contrasted with having generalized from experience) that the velocity of an object in free fall is

independent of its mass, predicts that the blocks will fall at the same rate. This prediction is in conflict with the experienced-derived rule that heavy objects fall faster. Again, however, the speed-force relationship is invoked in this instance to produce the proposition, gravity pulls equally on all objects regardless of their mass.

We have evidence from observations made during instruction that the proposition that all objects fall at equal rates is one that students don't quite believe. It is contradictory to the experienced-based schema and, thus, is not easily assimilated. Since the proposition that gravity pulls equally on all objects is predicated on an assumption which is weakly assimilated to the schema, schema theory would predict that the proposition will be easily rejected by the students.

In contrast, consider the proposition that gravity pulls harder on an object as it gets closer to the earth. This misconception is based on a rule that is generally accepted, even though the phenomenon is not directly observable. The force analysis of the general rule that the speed of objects increases in free fall produces the "gravity gradient" misconception. This misconception is based on an assumption that is easily assimilated into the experience-based schema and is also consistent with the force-speed relationships. For these reasons, schema theory predicts that the conception will be more tenaciously held.

Schema theory suggests that students' interpretations of instructional experiences will be influenced by their conceptions of the situation. There is evidence from this study that this is the case. An individual responsible for instruction must, therefore, be cognizant of the probability that students' interpretations of instructional events will not match the instructor's

interpretations. This suggests that provision must be made in instruction to insure that students' observations and interpretations of experiments are carefully monitored and inconsistencies in observations or interpretations addressed. Student exercises like the DOE Task furnish information (for example, see Findings 3, 4, 7, 8) that has potential use in monitoring students' interpretations of instructional experiences. The information provides a framework that facilitates the identification of inconsistencies between students' and instructors' interpretations.

Once inconsistencies are identified, the instructor can describe the relationship between the interpretation and a motion schema consistent with it. Then the essential similarities and differences between the schemata can be described. Recognition that alternative conceptions of the causes of motion are possible, elaborated by the knowledge of specific differences in the conceptions should facilitate the development of the Newtonian perspective as a distinct schema for the analysis of the motion of objects.

In the present study we saw how distant the concepts and formalism of classical Newtonian mechanics are from the motion-of-objects schemata of the students. Not one of the students conceived of motion in Newtonian terms, either before the instruction started or when they were doing experiments in the program's subsequent sessions. We have seen that the speed-force relations are pervasive in the students' schemata. However, the distinction between speed and acceleration, the central kinematic construct of classical mechanics, is elusive to students. Also students do not differentiate between speed and velocity.

This suggests that instruction must focus on the fallacy of the speed-force relations and also help students differentiate between speed and velocity and between speed and acceleration. Precise descriptions of the concepts and

propositions about motion currently in the students' schemata can help the instructor to design instruction that is meaningful to the student in terms of his or her current schema but still disturbs the schema to the extent that the student is motivated to seek, or becomes receptive to, an alternative conceptualization. We have some indications that several of the techniques and procedures used experimentally in the present study can become the elements in instructional design whose end-in-view is students' reconceptualization of motion. Certainly, the ConSAT and DOE Tasks can become student exercises through which descriptions of the students' schemata are obtained. Other exercises based on the ConSAT can be devised where the student arranges a set of terms about motion in a pattern that he or she can explain, and then must deliberately rearrange the terms in a different but still meaningful pattern. Another element would be to deliberately design a supportive environment where the students can be comfortable in discussing and testing out solutions to specific conceptual problems about motion.

Footnotes

1. An undemonstrated proposition concerning an undefined set of elements, properties, functions, and relationships: postulate.

2. According to the specifications of the State of Pennsylvania, the minimum IQ for the academically-talented designation is 135 on the Binet.

3. Viewing the DOE Task as a tool to elicit the students' underlying knowledge structures allows us to incorporate these inferred propositions in our analysis. Any evidence is admissible when seeking a description of knowledge. The inferred propositions are as much a component of the students' belief systems as are the explicity stated ones. It is only that their empirical justification is weaker.

4. A few propositions are shared rather than complementary propositions. The shared propositions include two types--one is trivial, the other not. The trivial ones are the givens of the experiment, such as "the distance from the red to the green is greater than the distance from thc red to the blue," or common definitions of terms. (Only one is listed.) The other exception is the generalized proposition that the strength of the applied force (force due to gravity) is

related to the resultant speed of motion. This proposition is certainly sensible, within the realm of everyday experience, and, as written, is essentially correct.

5. Data from two students do not appear in Table 11: DX was eliminated because of an uninterpretable prediction, and HT because the explanation rendered the prediction equivocal. HT predicted equal times to fall because the blocks "are not falling very far so the difference in time would not be very big." Formal propositions from these two students appear in Appendix C.

6. A definition can be "wrong" because it contains errors (that is, incorrect propositions) or because it is incomplete. We define a definition that contains no errors as "errorless" even if it is "incomplete," that is, missing some significant propositional information.

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Appendix A

Description of the Mechanics Simulation

In the mechanics simulation, students carry out computer-simulated experiments on an apparatus that physics teachers often use to help students understand how and why objects move.

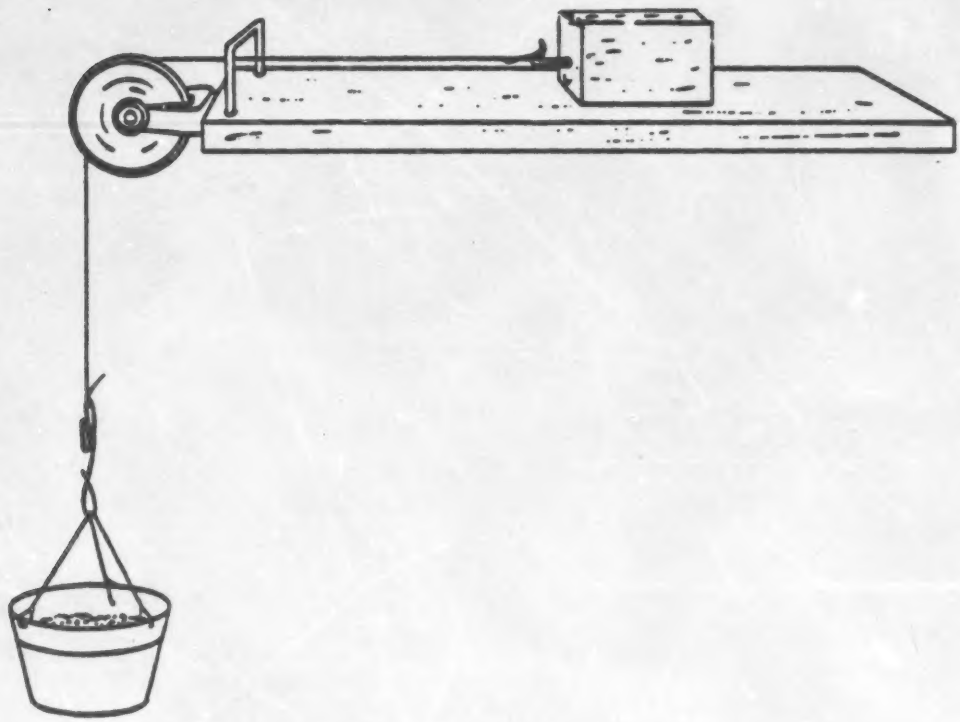

Figure A1

The A-Machine

The apparatus consists of a block of wood, a flat board with a pulley attached to one end, a string, and a bucket of sand (see Figure A1). The block of wood rests on the board and is connected to the suspended bucket

of sand by the string which runs over the pulley. From observations of the apparatus, it is possible to derive the empirical relationships that describe the motion of the apparatus. To derive these empirical relationships, many observations must be made and experiments set up, which is time-consuming.

The Mechanics Simulation allows physics students to do the experiments and obtain data in a way which would be unwieldy, and difficult using the actual apparatus. The purpose of the experiments is to gather data from which the empirical relationships describing the block's motion can be derived. Both the kinematic and dynamic relationships are investigated. The simulation provides the opportunity to observe the motion of the apparatus under many different conditions. Several features of the apparatus can be varied. These features include the mass of the block, the mass of the bucket of sand, the distance the block has moved along the board before the string is cut (or not cut), and the surface of contact between the board and block (rough or smooth). For each of these features, a value is specified by the student when setting up a simulated experiment with the apparatus.

As a part of each simulated experiment, the motion of the block and the bucket of sand are displayed by the computer on the Graphics Scope (see Figure A2). The block's motion in a given experiment will vary as a function of the mass of the block and sand, the coefficient of friction between the surfaces of the block and board, and the point where the string connecting the block and bucket is cut. The empirical relationships among these variables are what the students are seeking to establish by means of the simulation.

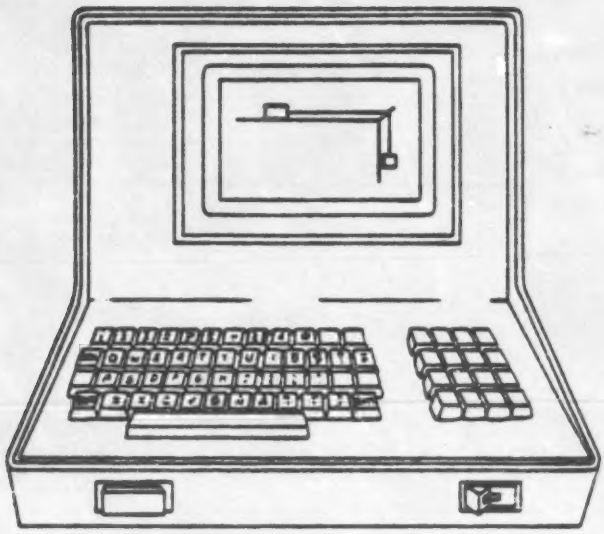

Figure A2

Graphics Scope

Not only does the computer display the motion of the apparatus under many different conditions, it also provides the student with a series of "snapshots" showing the position of the front edge of the block at equal time intervals along its path.

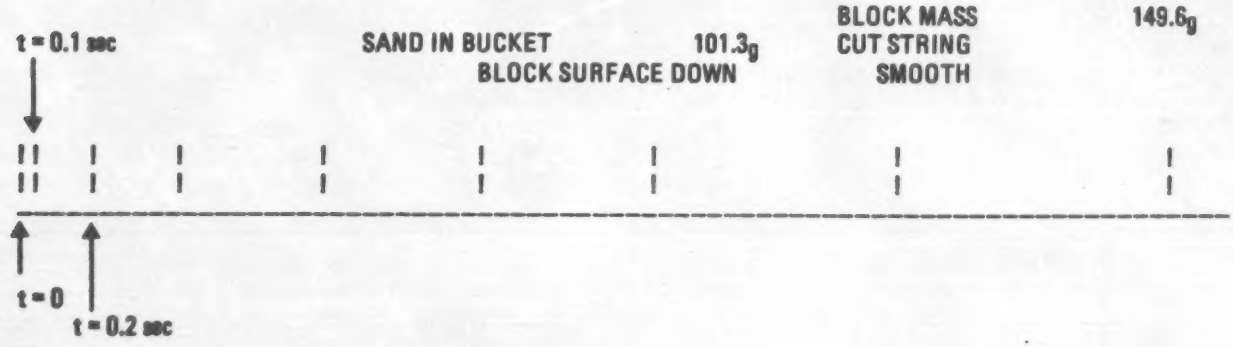

Figure A3

Figure A3 shows the computer printout of the "snapshots" at nine different times, from t = 0 sec to t = 0.8 sec. The block mass is 149.6 grams, the mass of sand is 101.3 grams, and the smooth side of the block is in contact with the board. From the "snapshots" printout, the student can measure the distance the block has moved in a given time interval and calculate the block's velocity and acceleration.

In addition to simulating the motion of the apparatus as it would be observed in the "real" world, the computer simulates the motion of the apparatus in three imaginary worlds. One of the imaginary worlds is Newtonian but frictionless and two of the imaginary worlds are Aristotelian, one with friction and the other frictionless.

In the Aristotelian worlds the "natural state" of a body is at rest. A body acquires a velocity as a result of an unbalanced force acting on it. In the Newtonian worlds the "natural state" of a body is a constant-velocity state. The velocity changes as a result of an unbalanced force.

The laws of motion can be formulated in several ways for the Aristotelian world. We chose two different ways, thus, distinguishing between two Aristotelian worlds, A and A'.

World A: Speed $\underline{v}$ is proportional to force $\underline{F}$ and inversely proportional to resistance $\underline{R}$ (or mass or other quantity--$\underline{R}$ will be allowed to stand for any or all of these). Thus:

$$v = k \frac{F}{R}$$

where k is a proportionality constant.

World A': Speed $\underline{v}$ is proportional to force $\underline{F}$ and inversely proportional to resistance $\underline{R}$, but no motion occurs at all unless $\underline{F/R}$ exceeds a minimum value of $\underline{\mu}$, which represents static frictional forces. Thus:

$$v = k \left(\frac{F}{R} - \mu\right), \frac{F}{R} - \mu > 0$$

$$v = 0, \frac{F}{R} - \mu \leq 0$$

The Newtonian worlds are distinguished in accordance with the presence or absence of friction.

World N: Acceleration $\underline{a}$ is proportional to the net applied force $\underline{F}$ and inversely proportional to mass $\underline{m}$. No frictional forces act. Thus:

$$a = \frac{F}{m}$$

World N': Acceleration is proportional to the difference between the applied force $\underline{F}$ and the frictional force $\underline{f_K}$ (the kinetic frictional force). However, if $\underline{v} = 0$, then $\underline{a} = 0$ unless $\underline{F}$ exceeds the maximum static frictional force f_S. ($v < 0$) is not allowed). Thus:

$$a = 0,\ v = 0 \quad F - f_S \leq 0$$

$$a = \frac{F - f_K}{m},\ v > 0$$

The Aristotelian worlds are called STAGIRA (the ancient Greek colony where Aristotle was born) and PHILOPONUS (the name of a critic of Aristotle's ideas about motion). The Newtonian worlds are called WOOLSTHORP (Newton's birthplace in England where he wrote Principia) and RAMETRIFAR (an anagram for terra firma).

The computer also has the capability of displaying and printing position-time and velocity-time graphs and data tables of the block as it moves along the track. When the student asks the computer to display and printout graphics plots, two lines will be traced on the Graphics Scope, one showing the velocity-time curve and the other the position-time curve for the block. These graphs are then produced as printouts (see Figure A4 as an example).

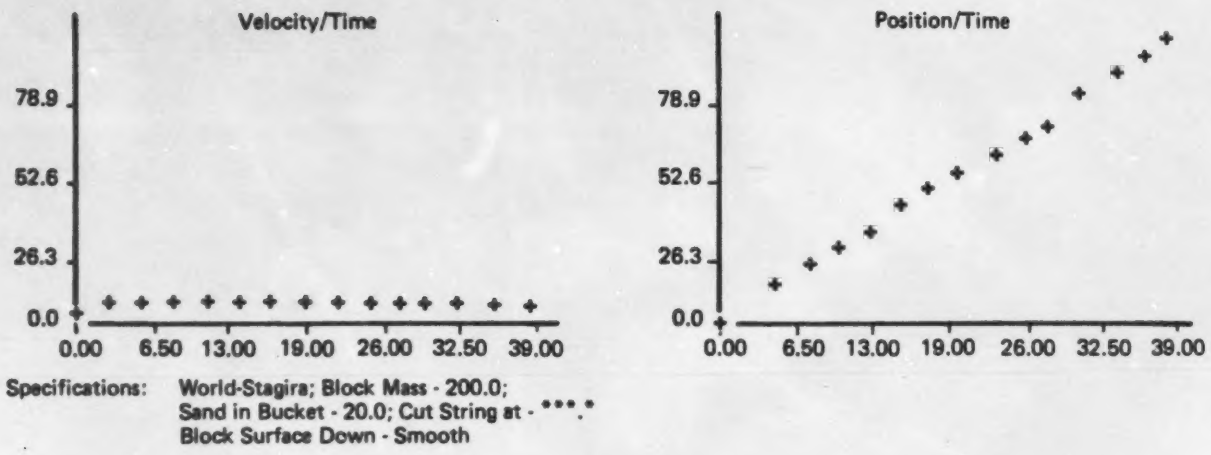

Figure A4

When the student asks the computer to display and printout plots, the Terminal produces a data table showing the velocity and position of the block in 60 evenly spaced time sequences (see Figure A5).

World Stagira Block Mass 200.0
Sand in Bucket 28.0 Cut String at ****.*
Block Surface Down Smooth

Time	Velocity	Position	Time	Velocity	Position
0.00	0.00	0.00	20.15	2.37	47.86
0.65	2.37	1.54	20.80	2.37	49.40
1.30	2.37	3.09	21.45	2.37	50.94
1.95	2.37	4.63	22.10	2.37	52.49
2.60	2.37	6.18	22.75	2.37	54.03
3.25	2.37	7.72	23.40	2.37	55.58
3.90	2.37	9.26	24.05	2.37	57.12
4.55	2.37	10.81	24.70	2.37	58.66
5.20	2.37	12.35	25.35	2.37	60.21
5.85	2.37	13.89	26.00	2.37	61.75
6.50	2.37	15.44	26.65	2.37	63.29
7.15	2.37	16.98	27.30	2.37	64.84
7.80	2.37	18.53	27.95	2.37	66.38
8.45	2.37	20.07	28.60	2.37	67.93
9.10	2.37	21.61	29.25	2.37	68.47
9.75	2.37	23.16	29.90	2.37	71.01
10.40	2.37	24.70	30.55	2.37	72.56
11.05	2.37	26.24	31.20	2.37	74.10
11.70	2.37	27.79	31.85	2.37	75.64
12.35	2.37	29.33	32.50	2.37	77.19
13.00	2.37	30.88	33.15	2.37	78.73
13.65	2.37	32.42	33.80	2.37	80.28
14.30	2.37	33.96	34.45	2.37	81.82
14.95	2.37	35.51	35.10	2.37	83.36
15.60	2.37	37.05	35.75	2.37	84.91
16.25	2.37	38.59	36.40	2.37	86.45
16.90	2.37	40.14	37.05	2.37	87.99
17.55	2.37	41.68	37.70	2.37	89.54
18.20	2.37	43.23	38.00	2.37	90.25
18.85	2.37	44.77	**.**	****.**	****.**
19.50	2.37	46.31	**.**	****.**	****.**

Figure A5

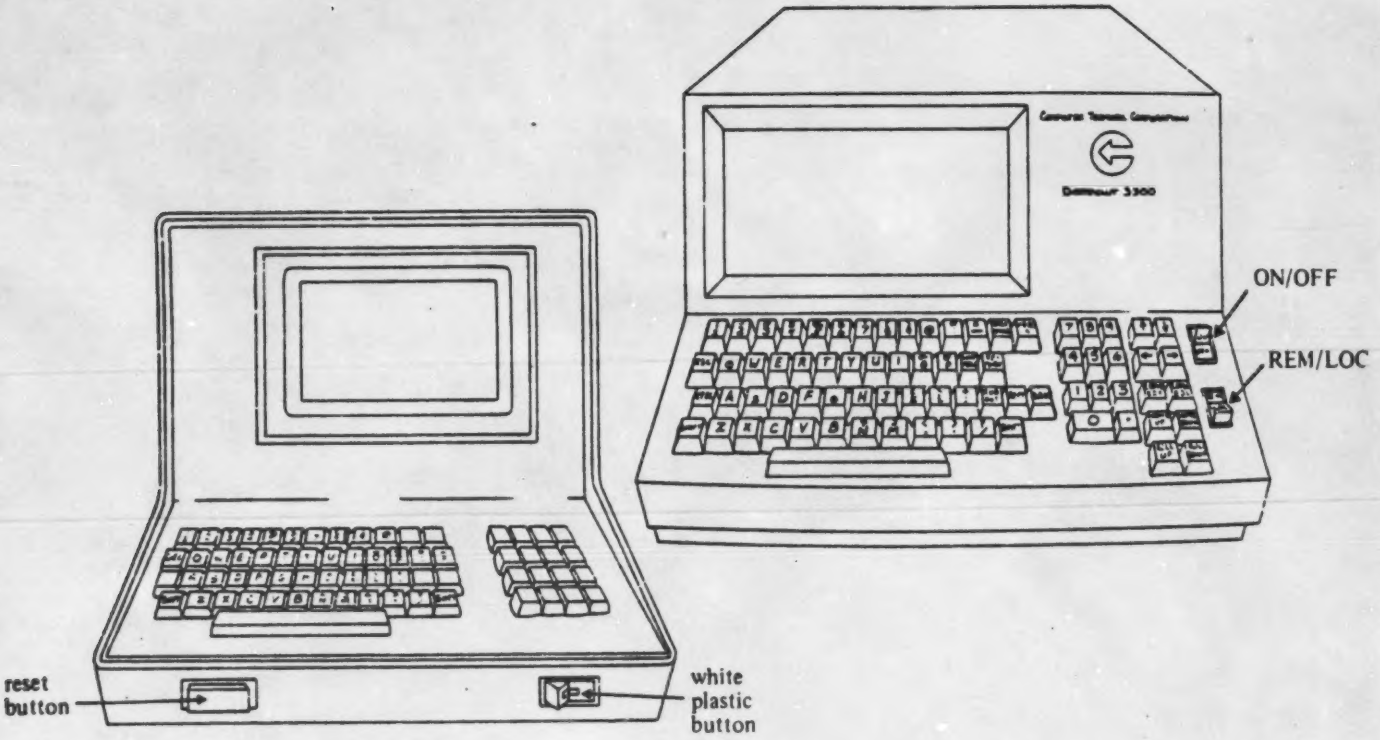

Figure A6

Graphics Scope and Data Point 3300 Terminal

The specifications for an experiment are put into the computer system using the Data Point 3300 Terminal which receives typed messages and displays data tables and graphs. The Graphics Scope displays the moving pictures of the apparatus. To conduct an experiment, the student specifies the conditions for the experiment and the desired output.

These are the specifications for a typical experiment:

(1) World - RAMETRIFAR

(2) Block Mass - 7.5 grams

(3) Sand in bucket - 7.0 grams

(4) Cut String At - 99.9 cm (This instructs the computer not to cut the string at all. An instruction of 25.0 cm for example, means to cut the string after the block has moved 25.0 cm).

(5) Block Surface Down

(6) Scale of Motion - "real" time (The motion of the apparatus can be displayed in "real" time or "slow motion".)

After setting up the experiment, the student asks the computer to display the motion of the apparatus on the Graphics Scope (Figure A6). Next, the student selects from the following Output Options:

(1) Display Snapshots - A series of lines taken at equal time intervals of .1 seconds, showing the location of the front of the block as it moves along the track (Figure A3).

(2) Display Graphic Plots - The student watches the tracing of graphs of the changing velocity and position of the block as it moves along the track (Figure A4).

(3) Output Plots - The position-time and velocity-time graphs are displayed on the Terminal screen. These can also be printed out if requested.

(4) Output Tabular Data - A data table is displayed, giving the velocity and position of the block in 60 evenly spaced time sequences. This can also be printed out (Figure A5).

Appendix B

Formal Propositional Translations of Student Protocols for the DOE Task on the Speed of a Single Object in Free Fall

Subject	Verbatim Protocol	Explicit Propositions	Inferred Propositions
TM	The eraser went faster as it passed the green mark than the blue. (I considered) the speed the eraser picked up as it came closer to the ground, the gravitational pull became greater.	$S_g > S_b$ $S \propto d$ $F_G \propto d$	$d_{rg} > d_{rb}$ $S \propto F_G$
FO	It gets faster because it picks up momentum and raises its speed when passing the green mark. (I considered) that the gravity pulls it faster toward the center of the earth and the green mark is closer to the center of the earth.	$S_g > S_b$ $S \propto d$ $S \nleftrightarrow F_G$ $d_{rg} > d_{rb}$	$S \propto F_G$ $F_G \propto d$
DY	It starts falling very slowly but it speeds more as it comes to the ground. The closer the force of attraction, the quicker the object will come down. (I considered) the speed of the eraser falling. Also, the force of gravity.	$S_g > S_b$ $S \propto d$ $S \nleftrightarrow F_G$	$d_{rg} > d_{rb}$ $F_G \propto d$
WD	The speed at the green mark is larger. The force of gravity accelerates the eraser, and since the green mark is farther down, it takes longer to reach the green mark than it does blue, so more acceleration takes place.	$S_g > S_b$ $S \nleftrightarrow F_G$ $S \propto F_G$ $d_{rg} > d_{rb}$	$S \propto d$
MD	It passes the blue mark at a slower rate than it passes the green mark. I considered what I watched and the pull of gravity on the eraser.	$S_g > S_b$ $S \nleftrightarrow F_G$	$S \propto d$ $d_{rg} > d_{rb}$
ST	The speed of the eraser increased as it went from the blue to the green because the distance from red to blue is less than red to green. The greater the distance the faster the speed. (I considered the) speed of the eraser and the distance from red to blue and red to green.	$S_g > S_b$ $d_{rg} > d_{rb}$ $S \propto d$	
KQ	The speed increases as it goes along. It is faster at the green mark. I considered what Galileo said, which is that falling objects increase their speed in relation to the time they have been following (sic). (The student later retracted the words "what Galileo said which is")	$S \propto d$ $S_g > S_b$ $S \propto t$	$d_{rg} > d_{rb}$

Subject	Verbatim Protocol	Explicit Propositions	Inferred Propositions
NJ	The speed of the eraser when it passed the green mark had increased since it passed the blue mark.	$S_g > S_b$	
	The farther the eraser has to go the more speed it will pick up.	$S \propto d$	$d_{rg} > d_{rb}$
LL	I don't know, it would seem that it would be faster because it had fallen faster but it didn't look that much faster. (I considered) the speed as it passed the area between the red and blue marks and the blue and green marks.	$S_g > S_b$ $S \propto d$ $S = \Delta d/\Delta t$	$d_{rg} > d_{rb}$ $t_{rb} > t_{bg}$
DC	When the eraser fell, the speed of its passing the green mark was significantly greater than its speed when passing the blue mark. When answering, I considered the time the eraser took to fall two similar distances based upon my observation while the experiment was in progress.	$S_g > S_b$ $d_{rb} = d_{bg}$	$S = \Delta d/\Delta t$ $t_{rb} > t_{bg}$
SD	The speeds are the same when it passes the blue mark and when it passes the red (sic) mark. I considered what I saw and that I think I remember the pull of gravity always stays the same no matter whether the object is just starting to fall or has been falling for a time.	$S_g = S_b$ $F_G \not\propto t$	$F_G \not\propto d$ $S \leftrightarrow F_G$ $S \not\propto d$ $d_{rg} > d_{rb}$
HT	When it passed the blue mark its speed was not much different than the speed when it passed the green mark. It didn't fall too far, so it didn't pick up that much speed.		

Appendix C

Formal Propositional Translations of Student Protocols for the DOE Task on Two Falling Objects of Unequal Mass

Subject	Verbatim Protocol	Explicit Propositions	Inferred Propositions
DC	**prediction:**		
	The ratio of speed between the aluminum block and the lucite block will be different with the former falling faster than the latter. This inference was made on the basis that the gravitational attraction will act greater upon the aluminum block than the lucite block because of the aluminum block's greater mass.	$S^A \neq S^L$ $S^A > S^L$ $F_G^A > F_G^L$ $m^A > m^L$ $F_G \propto m$	$S \equiv d/t_{of}$ $t_{of} \propto m$ $S \propto F_G$ $S \propto m$
	observation:		
	The blocks fell at roughly the same speed, however there was a very slight difference of speed, the aluminum block was a very minimal amount ahead. The first prediction was off because I did not take into account the distance in which the blocks were falling from. A great distance would probably be necessary for the greater rate of speed of the aluminum block.	$S^A \simeq S^L$ d_{of} is too small	$S \propto m$
MD	**prediction:**		
	I think the aluminum block would fall faster and hit the ground before the lucite. Because the aluminum block is heavier so it would have a stronger pull of gravity.	$S^A > S^L$ $t_f^A < t_f^L$ $w^A > w^L$ $F_G^A > F_G^L$ $F_G \propto w$	$S \equiv d/t_{of}$ $w \equiv m$ $t_{of} \propto m$ $F_G \propto m$ $S \propto m$
	observation:		
	I saw the aluminum block and the lucite block both hit the ground at the same time. (The reason must be) because the gravity pull was the same.	$t_f^A = t_f^L$ $F_G^A = F_G^L$	$F_G \not\propto m$
SD	**prediction:**		
	They will hit the floor at the same time. I forget the guy's name but when he was little he dropped two objects of different weights out of a church window and they hit the ground at the same time.	$t_f^A = t_f^L$ $w^1 \neq w^2$ $d^1 = d^2$ $t_f^1 = t_f^2$	$d/t_{of} \equiv S$ $w \equiv m$ $t_o^1 = t_o^2$ $t_{of} \not\propto m$ $S \not\propto m$
	observation:		
	same		

Subject	Verbatim Protocol	Explicit Propositions	Inferred Propositions
WD	**prediction:** The two blocks will take the same amount of time to reach the bottom. All masses reach the bottom at the same time, providing that there is no air resistance and that they are dropped at the same time and heighth (sic). **observation:** same	$t_{of}^{A} = t_{of}^{L}$ $m^1 \neq m^2$ $t_f^1 = t_f^2$ if $d^1 = d^2$ and $t_o^1 = t_o^2$	$t_{of} \equiv S$ $t_{of} \not\propto m$ $S \not\propto m$
NJ	**prediction:** They will both take the same amount of time to get to the ground. Newton discovered that whatever it is it will hit the ground the same time as something else even a different weight. **observation:** same	$t_{of}^{A} = t_{of}^{L}$ $w^1 \neq w^2$ $t_f^1 = t_f^2$ $t_{of} \not\propto w$	$t_{of} \equiv S$ $w \equiv m$ $S \not\propto m$
LL	**prediction:** They will both hit at the same time. I can't explain why it is just that I learned that somewhere. What I learned, I think it was in science, I got it, somebody a long time ago dropped a feather and a brick from a certain height and they hit at the same time, gravity exerts the same amount of pull on something no matter what its mass is. **observation:** same	$t_f^{A} = t_f^{L}$ $d^{feather} = d^{brick}$ $t_f^{feather} = t_f^{brick}$ $F_G = k$ $F_G \not\propto m$	$d/t_{of} \equiv S$ $t_{of} \not\propto m$ $S \not\propto m$ $S \leftrightarrow F_G$
TM	**prediction:** The aluminum block will fall faster because of the greater weight, gravity will make the aluminum fall faster. (I made a prediction) from experience such as a brick compared to a feather. The brick will fall faster. **observation:** From all that I could see they fell at about the same rate. I think that I was thinking that they were closer in weight than I thought.	$S^{A} > S^{L}$ $w^{A} > w^{L}$ $S^{A} \propto w^{A}$ $S \leftrightarrow F_G$ $S^{brick} > S^{feather}$ $S^{A} = S^{L}$ $w^{A} \simeq w^{L}$	$S \equiv d/t_{of}$ $w \equiv m$ $t_{of} \propto m$ $S \propto m$ $S \propto m$

Subject	Verbatim Protocol	Explicit Propositions	Inferred Propositions
FO	**prediction:**		
	Time for the aluminum block: about 1 second. Time for lucite block: about 1 1/2 seconds. Comparison: aluminum should be quicker to the floor than lucite because its heavier. I considered the weight of the two objects combined with the gravitational pull.	t_{of}^{A} = 1 sec t_{of}^{L} = 1 1/2 sec $t_{of}^{A} < t_{of}^{L}$ $w^{A} > w^{L}$ $t_{of}^{A} \propto w$ $w \leftrightarrow F_G \leftrightarrow t_{of}$	$d/t_{of} \equiv S$ $w \equiv m$ $S \propto m$ $S \leftrightarrow m \leftrightarrow F_G$
	observation: The aluminum block and the lucite block both hit the ground at the same time and also touched in mid-air. The gravity pulls objects equally regardless of weight, and the volume does determine the motion.	$t_f^{A} = t_f^{L}$ $F_G \propto w$ $V \leftrightarrow S$	$F_G \not\propto m$ F_G = k for all m $S \propto F_G$
KQ	**prediction:** They will both land at the same time. Gravity has an equal effect on things. They were both at the same height. They were pulled down at the same rate.	$t_f^{A} = t_f^{L}$ $d^{A} = d^{L}$ $S^{A} = S^{L}$ $S \leftrightarrow F_G$	$d/t_{of} \equiv S$ $F_G \not\propto m$ $S \not\propto m$ $t_{of} \not\propto m$ $S \propto F_G$
	observation: same		
JT	**prediction:** They should hit the floor at the same time. They are not falling very far so the difference in the time would not be very big.	$t_f^{A} = t_f^{L}$ d_{of} is too small $t_{of} \leftrightarrow d_{of}$	$d/t_{of} \equiv S$ $S \leftrightarrow d$
	observation: same		
ST	**prediction:** The times should be the same if they are both released at the same time. On the basis of Newton's law no matter how dense or big an object is if both are left go the same, the time should be the same.	if $t_o^{A} = t_o^{L}$ then $t_f^{A} = t_f^{L}$ and $t_{of}^{A} = t_{of}^{L}$ $t_{of} \not\propto D$ $t_{of} \not\propto V$	$d/t_{of} \equiv S$ $D \equiv m$ $S \not\propto m$ $S \not\propto V$
	observation: same		

Subject	Verbatim Protocol	Explicit Propositions	Inferred Propositions
DY	**prediction:** I think that the aluminum block will fall starting slower than the lucite, since it is heavier. The lucite block probably will stay about the same speed. The gravity of two larger objects should be less because of the pulling.		

Appendix D

Explanation of Symbols Used in Formal Propositional Translations of Student Protocols

Superscripts identify the object. The superscript ^{A} refers to the aluminum block; ^{L} to the lucite block. Subscripts identify the points at which measurements are taken. The subscript $_{r}$ indicates the red marker (the uppermost mark) on the pole used in demonstrations; $_{b}$ indicates the blue marker in the middle, and $_{g}$ the green marker near the floor.

time

- t - elapsed time, a variable
- t_{xy} - elapsed time in traveling from point x to point y; for example, t_{rg} is the time taken by an object to travel from the red marker to the green marker
- t_f - clock time at final point of motion (usually at the floor)
- t_o - clock time at original point of motion (release point)
- t^A - time in reference to the aluminum block
- t^L - time in reference to the lucite block
- Δt - change in time

distance

- d - elapsed distance, a variable
- d_{xy} - elapsed distance from point x to point y; for example, d_{rg} is distance from the red to the green marker
- d_{fo} - distance from floor to falling object, a variable
- d^A - distance in reference to the aluminum block
- d^L - distance in reference to the lucite block
- Δd - change in distance

object properties

- w - weight of object
- w^A - weight of aluminum block
- w^L - weight of lucite block
- m - mass of object
- m^A - mass of aluminum block
- m^L - mass of lucite block
- V - volume of object
- D - density of object

motion descriptors

- S - speed
- ΔS - change in speed
- S_x - speed at point x; for example, S_r refers to an object's speed at the red marker.
- S_{xy} - average speed to travel from point x to point y; for example, S_{rg} refers to the object's average speed in traveling from the red marker to the green marker
- a - net increase in speed, which the students call acceleration

force

F_G - force of gravity

relationships

$\propto$ - The two variables increase or decrease together; the relationship is roughly proportional, all other things being equal. The relationship is not necessarily commutative. That is, $x \propto y$ does not imply $y \propto x$.

$x \propto 1/y$ - As x increases, y decreases. See $\propto$.

$\not\propto$ - The two variables do not increase or decrease together. The relationship is not proportional.

$\simeq$ - The two variables are approximately equal.

$\equiv$ - The variable on the left is defined the same as the variable on the right.

$\leftrightarrow$ - The two variables are related, but the nature of the relationship is unspecified.

$\not\leftrightarrow$ - The two varibles are not related.

APPENDIX E

PHYSICS BACKGROUND OF THE DOE TASK DEMONSTRATION

This appendix provides background physics on both DOE tasks as an aid to readers whose physics knowledge is rusty. It also contains an alternative explanation of both tasks, based on common misconceptions of the students.

The demonstration in the DOE Task on the Speed of an Object in Free Fall is explained by Newtonian physics as follows. The eraser drops through the distance of 1 meter so quickly that it is virtually impossible to ascertain with the unaided eye whether or not acceleration occurred. Therefore, any definitive answer to a question about the eraser's speed is probably based on intuition, the application of a general empirically-based rule (informal knowledge), the application of a rule learned in some formal context (authoritative knowledge), or a force analysis of the physical situation. The force analysis is based on the assumption that there are only two forces that have an appreciable influence on the falling eraser. One is the gravitational attraction of the earth and the other, which is due to the air, is usually referred to as the "air resistance."

The gravitational force can be considered to be constant since the distance involved is small. A constant force produces a constant acceleration. Air resistance, however, places an upper limit on free-fall speeds (the terminal velocity). Once the upward force of

the air on the eraser equals the downward force of gravity on the eraser, the eraser will fall at a constant speed. Until these two forces are equal in magnitude, the eraser will continue to accelerate.

The question then becomes, has the eraser approached terminal velocity by the time it has fallen 1/2 meter? The answer is an empirical one, but a reasonable assumption is that the eraser will not reach terminal velocity within the first half-meter. Therefore, it will accelerate in the second half-meter, and its velocity as it passes the green marker is greater than its velocity as it passes the blue marker.

An alternative physical system is utilized by some of the students. The system has elements which are similar to some ideas of Aristotle concerning the motion of objects.

The basic notion of the alternative system is that objects are naturally at rest, and in the absence of any force, an object does not move. All motion, then, must have a cause, which usually is a force. A cart moving through the mud is pulled by the force of a horse, and a falling rock is pulled by the force of gravity. The object's motion is related to the force acting on it by the following general rule: $V = F/R$ where V is the velocity of the object, F is the force, and R is the resistance of the medium or friction. From this general rule, we see that two horses, which provide twice the force of one horse, can pull a given cart twice as fast, or can pull a cart against twice as much resistance (which may arise either from a heavier cart or from deeper mud).

In analyzing the first DOE task, the force of gravity and the

medium's resistance or friction are assumed to be constant at both the blue and green marks. Therefore, the velocity of the eraser at the blue mark is the same as its velocity at the green mark.

Physics background of the DOE Task on two falling objects of unequal mass.

The Newtonian explanation is as follows. There are two forces acting on each block: a downward force due to gravity, and an upward force due to air resistance. As a first approximation, the force due to air resistance can be ignored since it is small in comparison to the gravitational force.

The force of gravity acting on each block is proportional to the block's mass. A heavier block has a greater gravitational force acting on it than the lighter one has. However, the heavier block is more sluggish and resistant to being moved than the lighter one. A greater amount of force is needed to accelerate (change the speed or direction of motion) the heavier object. The degree of sluggishness or "inertia" is directly related to the block's mass.

So, although the force of gravity is greater on the aluminum block, a greater force is needed to accelerate it. The amount of gravitational force is directly proportional to the block's mass, and the block's inertia (resistance to being accelerated) is also directly proportional to its mass. These two factors exactly compensate each other, and the acceleration of both objects in free fall is the same (when air resistance is neglected, of course). Since the two blocks have the same acceleration, and travel the same distance, the time to fall to the floor will be the same for both.

The alternative explanatory system was described above, where the following formula was presented: $V = F/R$

For objects in free fall, the force is the force of gravity, and the R is air resistance. The magnitude of the force of gravity is the object's weight, and therefore the force on the aluminum block is greater than the force on the lucite block. Because the two objects have identical size and shape, the air resistance is (to a first approximation) the same, resulting in a predicted faster rate of fall for the aluminum block.